AD-A078 835 YANG (NAI C) AND ASSOCIATES NEW YORK F/G 13/2
NONDESTRUCTIVE EVALUATION OF AIRPORT PAVEMENTS. VOLUME I. PROGR--ETC(U)
SEP 79 N C YANG DOT-FA77WA-3964
UNCLASSIFIED FAA-RD-78-154-VOL-1 NL

1 OF 2
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A078835

Report No. FAA-RD-78-154 I

13

NONDESTRUCTIVE EVALUATION OF AIRPORT PAVEMENTS

VOLUME I

PROGRAM REFERENCES

BY

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SEPTEMBER 1979

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
18 FAA-RD-78-154-[redacted]VOL-1		

4. Title and Subtitle	5. Report Date
6 NONDESTRUCTIVE EVALUATION OF AIRPORT PAVEMENTS. VOLUME I, PROGRAM REFERENCES	11 Sep[redacted]79
	6. Performing Organization Code
	8. Performing Organization Report No.

7. Author(s)	
10 Nai C. Yang	

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Nai C. Yang & Associates, ~~Engineers, P.C.~~ SC 60 East 42nd Street New York, ~~N.Y.~~ 10017	11. Contract or Grant No. 15 DOT-FA77 WA-3964
	13. Type of Report and Period Covered

12. Sponsoring Agency Name and Address	14. Sponsoring Agency Code
U.S. Department of Transportation Federal Aviation Administration Systems Research & Development Service Washington, D.C. 20590	ARD-430

15. Supplementary Notes

12 174

16. Abstract

The concept of nondestructive evaluation and functional pavement design has been integrated in a computer program which is operational at Transportation Computer center in Washington, D.C. (TCC). The program logic and operational procedures are outlined in this report.

The NONDESTRUCTIVE TEST ~~The NDT~~ can be used as a substitute for the plate load test without interference to airport operation. All test data are processed and compiled in a NDT inventory file.

~~EVALUATION AND DESIGN~~ The strength of existing pavements is evaluated in terms of anticipated functional life as governed by cumulative stress damage and progressive surface deformation. The final program output is the cost information for ten design alternatives of equal functional performance.

VALIDATION PROGRAM Correlations have been made between the NDT data and subgrade geology, regional climate, airport operation, existing pavements and response of airport bridges. The current version of FAA standards is open to divergent interpretations and it does not indicate the cost effectiveness of a pavement program.

MATERIAL CHARACTERIZATION A universal testing procedure has been introduced to evaluate the dynamic response of pavement materials.

COMPUTER OPERATION Two operation manuals have been prepared for the execution on computer hardware system at TCC. The program is written in a high level language FORTRAN IV and involves extensive use of data storage and filing techniques.

17. Key Words		18. Distribution Statement
Computer Design	Cost Benefit	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.
Airport Pavements	Landing Gear	
Nondestructive Tests		
Material Characterization		

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	174	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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METRIC CONVERSION FACTORS

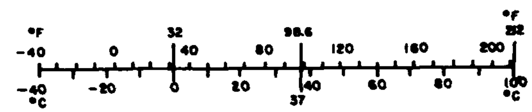
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SUMMARY

The concept of nondestructive evaluation and functional pavement design has been integrated in a computer program which is operational at Transportation Computer Center in Washington, D.C. The purpose of preparing this document is to familiarize airport engineers with the logic and operational sequence used in the computer program.

NONDESTRUCTIVE TEST The NDT is used as a substitute for the plate bearing test without interference to airport operation. The basic requirements of tester and testing procedures are specified in detail. The computer data processing consists of three sub-program: NDT1 to detect any system error and mistakes; NDT2 to reflect the reliability of data processing and NDT3 to establish a NDT inventory file.

USER'S REQUIREMENTS The purpose of functional pavements is to provide a safe and smooth surface for the operation of anticipated traffic which is expressed in terms of demand forecast, fleet composition, flight range, load factor and airport traffic distribution. The computer program will convert these data into an equivalent single type aircraft operation.

PRESENT FUNCTIONAL LIFE This subsystem evaluates the strength of existing pavement with respect to cumulative stress damage and progressive deformation of pavement structure. The present functional life is expressed in years as governed by these requirements.

COST BENEFIT ANALYSIS A universal design method is used to iterate the pavement component for all types of construction material. The final output of the program is the cost information for ten design alternatives of equal performance meeting identical requirements.

VALIDATION PROGRAM All data from five validation airports were processed by the computer program. Present functional life and cost benefit analysis are also processed for each airport. Correlations have been made with geology of subgrade, regional climate, airport operation, existing pavements and response of airport bridges.

CORRELATION WITH FAA STANDARDS A good correlation between FAA standards and functional pavement design shall depend on: (1) the selection of conversion factor from CBR to E-value and the CBR assignment for the soil classification, and (2) the reliability of structure coefficients and layer equivalencies. The current version of FAA standards is open to divergent interpretations and it does not indicate the cost effectiveness of a pavement program.

MATERIAL CHARACTERIZATION A universal testing procedure, similar to NDT frequency sweep method, has been introduced to evaluate the dynamic response of pavement materials at five validation airports.

COMPUTER PROGRAM An object level program is operational at Transportation Computer Center, TCC, in Washington, D.C. The program is machine dependent and needs periodic maintenance in updating the cost data and default values.

PART ONE EVALUATION PROCEDURE AND PROGRAM DESCRIPTION

INTRODUCTION

The concept of frequency sweep nondestructive evaluation of airport pavements was developed in 1967 for the pavement rehabilitation program at John F. Kennedy and Newark International Airports. A computer program was developed in 1969 and expanded in 1972 for the nondestructive evaluation of pavements at Portland International Airport, Oregon. The present computer format was finalized in 1975 for San Jose Municipal Airport. Many refinements have been incorporated into the computer program during its application to pavement evaluation at New Orleans and Cleveland Hopkins International Airports. For the current FAA validation program, the computer inputs have been standardized and system data files have been adopted to allow for more efficient program application to civil airports. In the future, a finite element program for solving layer discontinuities will be developed and incorporated into the computer program to analyze the structural details of concrete pavement. The purpose of preparing this program document is to familiarize airport engineers with the sequence of evaluation procedure and to describe the operational codes used in the computer program. The theoretical and conceptual background of the computer program can be found in references [1] and [2].

1.1. SYSTEM LOGIC

The computer program for nondestructive evaluation of airport pavements is coded as PAVBEN which includes the original program PAVDES developed in 1969 for Port Authority of New York and New Jersey. The current program is about 10,000 cards plus an average of 2,000 input cards. It is designed for both the UNIVAC 1108 and IBM 360 and requires about 300K in operation. Because of the program size and CPU time demands, over-night batch processing is the most practical operation at many IBM computer centers. Therefore, a system concept has been utilized in organizing the computer program. There are six compartments or subsystems in the program. The operational logic of these compartments is shown in Table 1.1. The first two compartments are operated separately to process NDT data from the field. The last compartment is a separate operation which is used only for the final detail design of pavement.

1.2. NDT DATA ACQUISITION

The purpose of NDT is to determine the deflection characteristics of a structure under the influence of external load. Because of its high degree of reliability, low cost and short testing time, NDT can be used to test many points to obtain quasi-static deflection similar to conventional plate load test. In planning data acquisition, the following guidelines shall be observed:

1. The NDT data shall be acquired, processed, analyzed and, then, incorporated in a mechanistic analysis program for evaluating the performance

Table 1.1 FLOW CHART OF PAVBEN COMPUTER PROGRAM

Job Inputs		Processing Program		Output Files		Decision Making
NDT Field Data	→	NDT1	→	Initial Processing	→	Error Analysis ↓ (to NDT2)
Existing Pavement	→	NDT2	→	Data in Groups	→	Test of Group Data ↓ (to NDT3)
		NDT3	→	NDT Inventory File ↓ (to PFL)		
Demand Forecast	→	PFL ↓	→	Present Functional Life		
Regional Cost Data	→	PAVDES	→	Cost Benefit Study	→	Fiscal Management ↓ (to GELS/FEM)
New Material Data	→	GELS/FEM	→	New Design Analysis	→	Engineering judgment ↓
						Final Pavement Design

of existing pavement. That means, the NDT data yield no direct information on existing pavement performance. The acquisition of NDT data shall be guided by the requirements of pavement design program.

2. Since many airport pavements were constructed in stages during airport growth, inherent variations are encountered in pavement composition, loading history as well as in ground support condition. The scattered performance of today's airport pavements can be positively identified only if adequate amount of data is acquired to optimize the evaluation inputs.
3. Because massive data acquisition is anticipated, the concept of statistical reliability shall be adopted in program planning.
4. Engineering disciplines shall be exercised to insure that (a) every NDT shall be needed for pavement evaluation; (b) every test shall have a complete set of data information; and (c) every bit of data information shall be processed and used as data inputs in pavement evaluation.
5. The entire NDT program shall be so scheduled that there will be no interference with the airport operation.
6. A small number of NDT may be reserved for research experiment if necessary.

1.2.a. BASIC REQUIREMENTS OF TESTER

Frequency sweep NDT uses a series of harmonic forces of constant amplitude vibrating steadily at all frequencies. Acquiring the dynamic response at various frequency including the response of first resonance

is vital to the outcome of the entire test. The variable frequency at constant dynamic load and other basic requirements govern the design of qualified testers.

STEADY STATE OF VIBRATION   The tester shall exert a constant forcing amplitude and a steady frequency at a test. The resultant ground acceleration or velocity is then integrated by an analog computer to determine the dynamic response (displacement) in the direction of forced vibration.

FIRST RESONANCE AND FREQUENCY RANGE   The quasi-static deflection determined by frequency sweep NDT is governed by summation of the pavement's dynamic response from its first resonance to infinity. For common pavement support, the first resonance is normally greater than 5 Hz which shall be the lower end of the frequency range of the NDT machine. The upper end of the frequency range shall theoretically be infinite. However, considering the practical mechanical constraints of vibratory equipment, an adequate vibrator shall be capable of testing at an upper end of frequency range of about 80 Hz. In order to maintain a reliable resolution, the vibrator shall be designed to have a range from 4 to 100 Hz.

VIBRATORY FORCE   The forcing amplitude shall be closely related to the aircraft wheel loads. Experience indicates that: (1) the heaviest wheel load of current modern aircraft is 56,000 pounds; (2) the ratio of natural frequency between aircraft tires and pavement support ranges from 1:6 to 1:4; and (3) the dynamic impact factor for a moving aircraft on smooth surface is 1.03. Using a damping coefficient of .05 for pavement, the magnification factor is about 10 when the forcing function vibrates steadily at the pavement system's first resonance, i.e., an NDT force of 5,800 pounds double amplitude will have an effect on the pavement system similar to an aircraft with a maximum dynamic wheel load of 58,000 pounds. This double amplitude of force shall be considered to be the minimum NDT requirement. For tests on heavy concrete pavements, the optimum forcing function can be as high as 10 kips peak to peak. The rated capacity of NDT machine shall be at least 1.2 times the upper range of the operational forcing function.

DYNAMIC RESPONSE   Prior to actual field testing in the NDT program, several series of load-frequency sweep tests shall be conducted on typical pavement to determine the optimum vibratory force and the size of load plate to be used for the program. The practical operational range will produce a dynamic response not greater than .005 inch at the first resonance vibration or smaller than .0002 inch at a steady state vibration of 60 Hz. Resolution of response monitoring system shall be designed for a rated range from .0001 to .01 inch. The size of load plate shall be 12, 18 or 30 inches in diameter. For NDT on pavements, an 18 inch diameter plate is generally used. For tests on subgrade, 30 inch plate will be used.

STATIC WEIGHT AND RESIDUAL FORCE   The vibrator's static weight also affects NDT reliability. To maintain a reasonable response output, the static weight of the vibrator shall be at least 33% greater than the effective vibratory force. Therefore, for airport pavement testing, the static weight of vibrator shall be about 14 kips.

1.2.b. PLANNING OF TEST

Adequate planning prior to field testing will have a significant effect on the quality and efficiency of NDT. Since each airport has its own unique operation condition, there can be no standard NDT program. The following guidelines can be used in planning field work.

1. Prior to the NDT location study, a review is required on the as-built condition of pavement facilities to locate the test points and to determine the number of tests.
2. An identification listing and drawing shall be prepared to indicate the test locations (see Tables 1.2 and 1.3).
3. In general, test location shall be spaced 200 to 300 feet apart within 2,000 feet of runway end, and 300 to 500 feet apart in the center portion of a runway or taxiway.
4. Additional tests shall be made in heavily trafficked areas and areas with known pavement problems.
5. For the major runway and taxiway areas, at least two tests shall be performed on every types of pavement. The test location shall be offset between 8 to 18 feet to the right or left of centerline of taxiway or runway and it shall not be on longitudinal joints or cracks of concrete pavement.
6. At least two cross-sections shall be taken for active runways having offset at intervals from centerline to pavement edge, The pavement response (deflection) in a strip 10 to 20 feet off the centerline can be 10 to 20% lower than on the centerline.
7. The as-is strength profile of a normal runway is also closely related to the longitudinal distribution of aircraft operations. At the end of a runway, take-off and landing impacts are significant and the dynamic response of pavements can be relatively low. In the mid-portion of runway, the effective aircraft weight is reduced because of wing lift at take-off speeds. The NDT data may show effects of different operations and, consequently, the data may be grouped according to various operation modes.
8. Theoretically, frequency sweep NDT measures quasi-static deflection of a pavement structure, including the subgrade's elastic property. In the computer program, the general eqilibrium of layered system will be used to separate the E-value of subgrade and pavement layers. It is desirable to group the tests by the type of existing pavements.

Table 1.2 LISTING OF NDT LOCATION

Test No.	Grid/Station/Offset			Date/Time	Temp.	Load/Rad.	PFLPAV
1	A	000+50	R12			/9.	CC7
2	A	002+50	L12			/9.	CC7
3	A	004+50	R12			/9.	AC2
8	A	015+00	L12			/9.	AC2
8-1	A	015+00	L06			/9.	AC2
8-2	A	015+00	L18			/9.	AC2

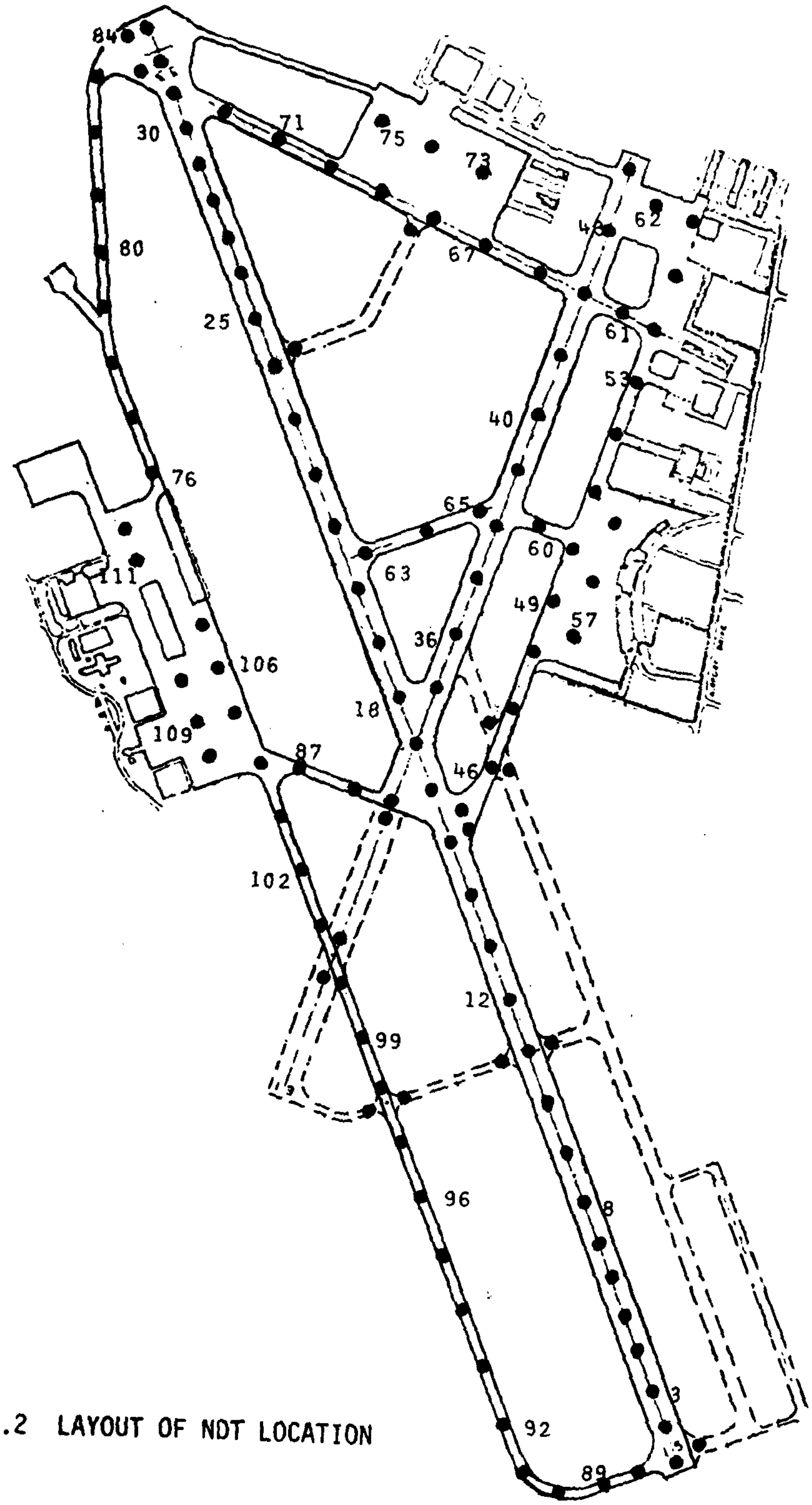

Table 1.2 LAYOUT OF NDT LOCATION

1.2.c. TESTING PROCEDURE AND DATA RECORDING

Actual testing procedures are outlined as follows:

1. Positive communication shall be established between the airport control tower and the NDT operator. A minimum 10 minute notice shall be obtained by the NDT operator for clearing the operational area to arriving or departing aircraft.
2. Important tests, such as those on runways where tower control is mandatory, shall be performed early in the testing program and preferably at night.
3. The system output shall be calibrated on a shaker table for forcing frequency, forcing amplitude and dynamic response (displacement). The pre-test calibration record shall be kept as an integral part of the data file.
4. No filters or dampers shall be employed for any forcing frequency so that all measurements reflect true dynamic response.
5. The equipment shall be warmed up prior to data recording.
6. The electric system shall be calibrated for both the force montoring and response integrator in the field twice a day.
7. Prior to a production run, load-frequency sweep test shall be conducted at defined locations to optimize the forcing function and size of test plate which will produce a response within the limits of .0002 to .005 inch.
8. The forcing function shall be set at a pre-defined, constant load level which shall always be of double amplitude. A variation of 5% is tolerable. For example, if the pre-defined constant load is 6,000 pounds, the actual load may range from 5,700 to 6,300 pounds.
9. The input force shall be maintained at a steady state of vibration for at least one second. The response (displacement) is then recorded.
10. For a complete frequency sweep test, steady state vibration shall be repeated at the following selected frequency interval:

Frequency Range	Intervals	Tolerance
5 to 15 Hz	1.0 Hz	±0.1 Hz
16 to 28 Hz	2.0 Hz	±0.4 Hz
30 to 80 Hz	5.0 Hz	±1.0 Hz

11. Any malfunction of equipment shall be recorded including change of calibration factor and the name of specialist who sponsored the change.
12. Pavement temperature shall be measured at several locations at two hour intervals during the testing period.
13. On the first batch of printouts, channel identification shall be made for frequency, forcing amplitude and response together with their respective calibration factors. All data shall be noted in the field log.
14. Visual observation shall be made by NDT operator at each test location on moisture and drainage condition of pavement surface. NORM means moist base and WET means water pockets on cracked pavement surface. NDT operator shall also sketch and note the pattern of pavement cracks, joint deterioration and general performance conditions of pavement at each test location.

1.2.d. CALIBRATION AND MONITORING TOLERANCE

For NDT, there are equipment calibrations for frequency, amplitude and integrated response. Calibration of the first two elements is relatively simple because a standard frequency and load analyzer can be utilized for the examination. As response (displacement) is normally obtained by integration of either the velocity or acceleration monitored at the test, there is no direct method of calibrating the monitored data with the actual ground displacement. The use of shaker table for calibrating velocity transducers is a reliable method in the laboratory. This calibration procedure is mandatory for transducers every three months and for any new transducers. During the production run, the electric monitoring system shall be shunted twice a day at zero and at the standard load setting to determine the calibration factors of electric system which will be used in equilizing the data inputs. The operational tolerance in gauge setting is 2% and 5% for forcing frequency and load amplitude respectively. The average monitoring time is about five minutes per test plus three to five minutes for moving from one test location to another.

1.3. NDT DATA PROCESSING

NDT data processing consists of three operation programs: NDT1 initial data process; NDT2 statistical processing; and NDT3 processing of NDT inventory file. There are three file systems: job inputs, default and computed inputs. The operation logic and sequence are shown in Table 1.4.

Table 1.4 FLOW CHART OF NDT DATA PROCESSING

Job Inputs	Default and Computed Files	Processing Programs	Output Files
Grid ID		NDT1	
Test ID	→	Initial Processing →	Graphic of Machine
NDT Calibration		Error Analysis	Data and E-value
NDT Machine Data			↓
		↓ NDT2	Graphic of Grouped
Facility & Group ID	→	Statistical Process →	Data and Profile
			↓
Existing	→	↓ NDT3	→ E-value of Subgrade
Pavements	PFLPAV (Default) →	General Equilibrium	
	Design Charts ←	of Layered System	
Drainage	→	GELS/NDT3	→ E-value of pavement
Condition			↓
			NDT Inventory File

1.3.a. INITIAL DATA PROCESSING

The first program of data processing is coded as NDT1. There are four input files: grid identification, test identification, NDT calibration and NDT machine data. Because of massive data inputs, rigid compliance to input format and data card preparation is necessary. The theoretical background of NDT1 processing program is given on pp. 9-10, Ref.[2]. The outputs of NDT1 consist of (1) a graphic display of the machine data which provides a visual reading of test result; (2) three data summaries sorted by test number, location and data/calibration for the purpose of identifying any mechanical or human mistakes during the test as well as in the data presentation; and (3) statistical correlation between E-value and DSM(W). The purpose of the NDT1 program is to detect any system error and mistakes prior to the second stage of data processing. It produces a summary of NDT data in which the most important column is SUMZ, the quasi-static deflection of pavement surface. An example of NDT1 output is shown in Table 1.5.

Table 1.5 SUMMARY OF NDT DATA ON PFLPAV (18. IN. PLATE) FOR STATISTICAL CORRELATION OF E AND DSM

TEST NO.	LOCATION STA OFFSET	DATE/ CALIB	TEMP DEGF	H(1) HZ	SUMZ E-6 IN/LB	DSM(W) KIP/IN	DSM(W) /E IN	E-VALUE
1-0	A015.0 R06	2/5	86.8	9.00	0.4447	450.	36.50	124934.
2-0	A033.7 R06	2/5		9.00	0.6345	3180.	36.32	87522.
3-0	A053.8 L06	1/1		9.00	0.5026	3400.	30.76	110536.
---	----.- ---	-/-		-.--	-.----	----.	--.--	------.
---	----.- ---	-/-		-.--	-.----	----.	--.--	------.
110-0	L096.0 X06	13/2		8.99	0.7949	2410.	34.48	69893.
111-0	L111.0 X06	13/1	69.8	9.00	0.7343	2860.	37.80	75661.
112-0	L126.2 X06	13/1		9.00	0.6797	2900.	35.48	81738.

	DSM(W)	DSM(W)/E	E-VALUE
Minimum Value :	330.	16.10	6859.
Maximum Value :	9200.	53.40	197431.
Mean Value :	3623.	40.20	88472.
Coef. of Variance :	. 59	.138	.418
Summation :	.605E06		.148E08
Sum of Square :	.265E10		.153E13
Sum of E-value x DSM(W) :	.635E11		
Number of Tests :	112		

Linear Correlation : E-Value = 21.67 x DSM(W) + 9952.
Correlation Coefficient : 0.97

1.3.b. STATISTICAL AND RELIABILITY ANALYSIS

The NDT2 processing program determines mean and standard deviation for groups in accordance with (1) the function of facility, (2) pattern

of aircraft movement, (3) history of pavement construction, (4) pavement composition, and (5) the range of E-values processed by NDT1. Some engineering judgment is required to define the existing pavement conditions as well as to project future rehabilitation requirements. On some occasions, it may be desirable to re-group the pavement facility and to re-run the NDT2 program to improve the meaning of data presentation. The output of NDT2 processing program is a graphic presentation of each individual E-value and the AREA-E which is equal to the mean value minus one standard deviation of E-values in each defined group. Statistically, the AREA E-value represents a reliability of .84. That means, 84% of individual E-values will be greater than the AREA E-value. An example of NDT2 output is shown in Table 1.6.

Table 1.6 NDT2 STATISTICAL PROCESS OF E-VALUES

```
                     RUNWAY 7L-25R/PROFILE

 LOCATION    E-VAL       AREA-E    EMIN= 4000.    ESTEP= 3000./.
 ...............................................................
                    . .  92279. .         .         .         .
A 00150R06  124934.                              X          * .
A 00337R06   87552.                             *X            .
A 00538L06  110536.                              X      *     .
                    . .  69566. .         .         .         .
A 00660R06   72969.                       X*                  .
A 00810X06   75098.                       X *                 .
A 00960X06   69893.                       X                   .
A 01110X06   75661.                       X *                 .
A 01262X06   81738.                       X   *               .
A 01315L06   71568.                       X*                  .
A 01470X06   70474.                       X                   .
A 01575X06   69516.                       X                   .
A 017 0X06   71894.                       X*                  .
```

1.4 INVENTORY FILE OF PAVEMENT SUPPORT

The outputs of NDT1 and NDT2 represent the load-deflection characteristics on the surface of supporting system which can be either existing pavement or prepared subgrade. The processed AREA-E-value represents the combination of: (1) the surface deflection of supporting system, (2) load intensity and size of plate, and (3) statistical reliability of a group of E-values. For tests on prepared subgrade, the AREA-E values can be directly used in mechanistic theory to determine pavement composition. For tests on existing pavements, computation experience indicates that the pavement AREA-E value can be used for concrete overlay design with no significant difference. However, for asphalt overlay design, the thickness of overlay layer is very sensitive to the E-value of subgrade. The NDT3 program is designed to transform the pavement E-value to E-value of its subgrade support. The process of transformation consists of:

1. Converting E-value according to Eq. 1.15a, Ref. [2], using (a) the radius of test plate, (b) the unit load on test plate, and (c) the surface deflection of pavement support;
2. Introducing the composition of existing pavement to indicate (a) the E-value of each layer components except the subgrade support, (b) the thickness of each layer components including infinite thickness for subgrade support, and (c) Poisson's ratio for each layer components to be assumed;
3. Determining the E-value of subgrade support by computer iteration using general equilibrium of layered system, GELS, (pp. 201-207 and 254-255, Ref. [1]).
4. Repeating the above three processes for the drainage condition observed in the field.

1.4.a. EXISTING PAVEMENT FILE

All NDT measurements taken on the pavement surface represent the total response of the pavement system including subgrade. Experience indicates that the subgrade deflection ranges from 80% to 95% with an arithmatic mean of 85% of the total deflection of a pavement structure. The general equilibrium of layered system (GELS) can be used to determine the E-value of subgrade. Computer analysis indicates that if the E-value of pavement layers is varied by 30%, the computed E-value of the subgrade varies only by about 5%. Therefore, exact characterization of pavement layers is less sensitive in deflection analysis than subgrade E-value characterization. Computer analysis also indicates that the thickness of pavement layers having an E-value greater than 200,000 psi is very important in deflection analysis. A properly documented as-built record will be very useful in NDT analysis. To simplify computer simulation, existing pavement constructions can be grouped into a default system as shown in Table 1.7. Except for a few special cases, engineering practice under the general FAA rule, both past and current, is considered in the formulation of this default system. The computer time, CPU, is about one minute in processing the subgrade E-values for an average two runway airport. On the other hand, if this default system is over-riden by the inputs of exact composition and E-values of existing pavements, the CPU time for such computer process will be 20 to 100 minutes depending on the number and layers of existing pavement system.

Table 1.7 DEFAULT SYSTEM OF EXISTING PAVEMENTS

PFLPAV	SUBGRADE	EXBSA	EXBSC	EXAC	EXPC	EXACOV	EXPCOV
E-Value	++++	50000	30000	140000	3000000	180000	4500000
AC1	INFI	6.		3.			
AC6	INFI	6.		20.			
CC3	INFI		8.		12.		
CC4	INFI		8.		14.		
CC7	INFI		8.		17.		
OC3	INFI		8.		12.	4.	
OC4	INFI		8.		10.	6.	
OC7	INFI		8.		12.	1.	6.

1.4.b. SUBGRADE SOIL AND PAVEMENT DRAINAGE RECORDS

In the NDT process, the condition of pavement support is characterized by its load-deflection behavior. The conventional soil classification and tests will have no direct contribution to pavement design analysis. However, the moisture change in subgrade will result in a significant variation in physical properties and drainage condition of pavement support. The degree of negative effect on pavement performance shall depend on the type of supporting soils. The FAA soil classification, in this respect, is useful and should be closely associated with the drainage condition of subgrade. A coefficient of dry-moist against wet-saturated condition will be assigned to a given soil classification.

1.4.c. NDT INVENTORY FILE

AREA E-value determined by the NDT2 processing program together with the existing pavement file form the inputs for the NDT3 processing program. The first step of this program retrieves the pavement deflection SUMZ in computer file and then uses the general equilibrium of layered system to estimate the subgrade E-value. The first output of NDT3 is the E-value condition at the test. Experience and many field measurements indicate that the E-value of subgrade under wet saturated or pumping condition ranges from .45 to .65 of a dry-moist base. In the NDT3 program, a default coefficient of .60 is used to convert the normal dry-moist subgrade E-value to a wet saturated one. This default value can be replaced by any value assigned by the designer. After the conversion, by this coefficient, the subgrade E-value is fed into GELS to iterate the surface deflection of pavement under modified base drainage conditions. The output of NDT3 reflects the base drainage conditions and is tabulated in the NDT inventory file which will be used for subsequent pavement design and evaluation (see Table 1.8). For an average two runway airport, the CPU time for the NDT3 program is about 20 minutes. In order to expedite the NDT3 operation, a set of design charts has been computed for the default system of existing pavements. By using these charts, interpolation between design curves will be a substitute for the iteration process by GELS. The computation time can then be reduced to less than one minute.

Table 1.8 NDT INVENTORY FILE

CODE	STA-FROM	STA-TO	EPAV NORM	EPAV WET	ESUB NORM	ESUB WET
RW 15-33	0.00	3.00	179545.	1 6703.	41967.	25180.
	3.00	69.00	34885.	24375.	18739.	11244.
	69.00	76.50	27745.	18585.	16548.	9929.
	76.50	80.00	165589.	111425.	36769.	22061.
RW 1-19	16.00	52.00	32267.	22780.	21111.	12667.
TW A	16.00	51.00	29191.	19662.	6290.	3774.
GATE/AP8N	26.00	35.00	21726.	14580.	11833.	7100.

1.5. EQUIVALENT SINGLE TYPE AIRCRAFT OPERATION

The NDT inventory file characterizes the strength of existing pavements. The pavement evaluation program is designed to determine the functional life of existing pavements under the present airport operations. The evaluation program consists of two sub-systems with the following computation flow:

Inputs	Processing Program	Outputs
User's Requirements Aircraft Operation →	Equivalency ↓ →	Single Type Aircraft Operation
NDT Inventory File →	Pavement Analysis →	Present Functional Life

The first subsystem is equivalent single type aircraft operation. Airport operations always consist of mixed aircraft. It is necessary in pavement analysis to convert these mixed aircraft operations into equivalent operations of a single type of aircraft. The computation flow is shown in Table 1.9. The concept of equivalency analysis is based on the assumption that if N-th movement of aircraft type A results in a cummulative pavement damage equal to M-th movement of aircraft type B, the operation of aircraft A is considered to be equivalent to (M/N) number of operation of aircraft B.

Table 1.9 EQUIVALENT SINGLE TYPE AIRCRAFT OPERATION

Default System Computed Inputs	Job Inputs	Processing Program	Output Files
	Average Daily Movement Aircraft Weight Airport Traffic Distribution →	↓	
Aircraft File →		Aircraft Characteristics → ↓	Aircraft Traffic Movement, ATM
System Default Values →		Load Repetition ↓	
Aircraft Weights Contact Radius Eq. Single Wheel APX, APY ↓	PFLPAV →	GELS/PFL ↓	
Stress and Deflection of PFLPAV →	Eq. Aircraft Facility ID Bandwidth → Forecast Service Year	Equivalency Analysis →	Equivalent Single Type Aircraft Operation AAND, AANS

In the equivalency analysis, the following two sets of job inputs are required:

1. Type of pavement to be designed for aircraft operation and its potential damage with respect to cummulative deformation and fatigue stress.
2. User's requirements on aircraft operation which will reflect the demand forecast, operational weight, utilization of public aviation facilities (PAF) and airport traffic distribution.

Detailed computer procedures are discussed under the following headings.

1.5.a. DEMAND FORECAST

The primary purpose of functional pavements is to provide a safe and smooth surface for the operation of anticipated traffic. During the functional life of pavements, there shall be no major maintenance which may interfere with the traffic operation. Therefore, the most important user's requirements are the demand forecast and traffic distribution on airport. Pavement computer analysis will be as accurate as user's inputs. Several guidelines shall be followed in preparing these inputs. There are many factors which will directly and indirectly contribute to the growth of airport traffic. A reliable demand forecast can be deduced from the study of these factors. To compensate for the risk of unknown factors in forecasting, the traffic volume used in pavement computer analysis will automatically reflect three possible forecast conditions: half, full and double demand operations.

DEMAND FORECAST OF AIR TRADE AREA The area demand is normally related to population, employment, per capita income, industry and commerce growth of the trade area, all of which is a dynamic economic system woven closely with national and regional development. A growth rate shall be used in forecasting the airport demand.

SCHEDULED AIR CARRIER At many civil airports, operation of scheduled air carriers contribute almost 98% major aircraft movement. GA, air taxi, charter and military aircraft operation contribute negligible effect on pavement structural performance both in number of movements and operational weight of aircraft. The fleet composition and growth trend of major air carriers shall be considered in the demand forecast.

PASSENGER SEAT CAPACITY The ATA forecast projects the annual average growth of emplanements and then develops the departure operation according to carrier fleet composition, stage length and aircraft capacity. The aircraft used in the ATA forecast are classified by seating capacity. The standard seating/size configuration of aircraft is assumed to be as follows:

Norminal Seating Capacity	Typical Aircraft Type
500	High capacity 747
350	Regular 747, high capacity tri-jet
250	Regular tri-jet
200	Stretched DC-8, A-300
150	New technology aircraft 767
125	Stretched 727, 707/DC-8, 757
100	727, stretched DC-9, 737
50/75	Small jets, props

OPERATIONAL WEIGHT OF AIRCRAFT The normal operational take-off weight is governed by the passenger load factor and flight range and is always lower than the maximum take-off weight designed by aircraft industry. In the computer program, the passenger load factor is simplified as "high" for a full load and "moderate" for 65% occupancy. The flight range is coded "Xlong" for overseas operation; "long" for coast to coast non-stop flight; "medium" for ranges between 1000 to 2000 miles and "short" for inter-city hops less than 1,000 miles. The computer inputs will be flight range and load factor for each type of aircraft instead of the weight of aircraft in thousands pounds (see Table 1.10). The computer program will automatically determine the aircraft weight at take-off, landing roll and touch-down operation according to Eqs. 2.1 and 2.2, Ref.[2].

Table 1.10 OPERATIONAL AIRCRAFT WEIGHTS

AIRCRAFT	RANGE	LOAD FACTOR	TOW	LRW	TDW
B747	LONG	HIGH	615000.	507852.	761777.
DC10/10	LONG	HIGH	390000.	337538.	506308.
L1011	LONG	HIGH	390000.	334750.	502125.
DC8(B707)	LONG	HIGH	325000.	242847.	364270.
B727-200	MEDIUM	HIGH	170000.	148587.	222880.
DC9(B737)	SHORT	HIGH	100000.	86000.	129000.

GENERAL AVIATION AND NON-SCHEDULED FLIGHTS The operation of general aviation and other flights may have a significant effect on the capacity of runway use but for all practical purposes these operations have no impact on structural integrity and functional performance of pavement system.

DEMAND FORECAST In considering all factors discussed above, the demand forecast in terms of aircraft movement can be tabulated for computer inputs. An example is shown as follows:

Table 1.11 ADM, AVERAGE DAILY MOVEMENTS*

Aircraft	1977	1978	1983	1988	1993	1999
B747	0	0	1	1	2	4
L1011	4	5	9	11	12	18
DC-8(B707)	14	13	8	2	0	0
B727-200	46	47	62	76	80	90
B727-100	32	36	40	38	36	32
DC-9(B737)	42	43	48	46	44	40
F-27	19	16	7	0	0	0
DC-X-200	0	0	2	20	44	47

*One aircraft movement = one landing and one take-off operation.

1.5.b. TRAFFIC DISTRIBUTION

Utilization of public aviation facilities (PAF) including runways, taxiways and holding pads shall depend on such factors as flight pattern, navigation system, runway-taxiway configuration and terminal complex.

Each airport has its own unique pattern of PAF utilization and traffic distribution which shall be properly analyzed prior to pavement evaluation. In general, the traffic distribution on a runway can be divided into three segments consisting of the touch-down zone at each end of a runway and the remaining center segment. In the touch down zone, the pavements are subject to severe landing impact, heavy take-off load and sharp braking thrust. The length of touch-down zone ranges from 2500 to 3000 ft. for heavily trafficked runway. The center segment of runway does not receive heavy loads but the moving aircraft can develop excessive vibration if the pavement surface in this segment is not smooth. On some occasions, if the after burner of a jet aircraft is low, the hot exhaust may burn the asphalt surface at the point of body rotation of a take-off aircraft. The function of runway pavements shall be designed for all these situations. Traffic distribution on taxiways and holding pads does not assume such distinctive patterns. However, more than 85% of a aircraft movement time, from gate position to take-off, or vise versa, is consumed on taxiways. Taxiway and holding pad pavements, consequently, receive the most severe loadings from aircraft in both operational weight and braking thrust. An example of Airport Traffic Distribution, ATD, is shown in Table 1.12.

Table 1.12 AIRPORT TRAFFIC DISTRIBUTION

ATD	ATDSUG	AIRPORT TRAFFIC DISTRIBUTION, SUGGESTED				
FACILITY	STA-FROM	STA-TO	YEAR	TOW%	LRW%	TDW%
1	000.0	030.0	1979	53.4	38.1	35.6
	030.0	095.9	1979	53.4	38.1	0.0
	095.9	120.9	1979	0.0	15.0	2.5
2	000.0	030.0	1979	9.2	40.3	37.8

AIRCRAFT TRAFFIC MOVEMENTS The first step of computer operation is to combine inputs ADM and ATD in determining the aircraft movements, ATM, according to facility location, service years and type of forecast which is proposed by ATA, Airport Authority or the consultants. The traffic movements in this output (see Table 1.13) represent the total number of take-offs, landing rolls or touch-downs for each type of aircraft in operation.

Table 1.13 AIRCRAFT TRAFFIC MOVEMENTS

FACILITY	SERVYR	FORECAST	STATION FROM-TO	B747	DC10/10
RW 25R-7L	1	FAMSUG	0.-30.	TOW:3.216E03	7.601E03
				LRW:2.295E03	5.424E03
				TDW:2.144E03	5.068E03
RW 25R-7L	1	FAMSUG	30.-96.	TOW:3.216E03	7.601E03
				LRW:2.295E03	5.424E03
				TDW:0.0	0.0

LOAD REPETITIONS The next step of computer operation is to determine the probability of wheel load repetition on runways and taxiways. The following controlling factors are involved in the probability determination:

1. Bandwidth	norm/visual or lights/ILS ground navigation
2. Radius	Radius of tire contact area
3. X	Transverse wheel spacing
4. Facility	RW, TW and HP
5. Y	Longitudinal axle spacing

AIRCRAFT FILE In the computer input storage, the characteristics of sixteen active aircraft have been compiled. An example is shown in Table 1.14A. The probability of wheel load repetition per take-off or touch-down at a pavement point is expressed by APX, Eq. 2.3, Ref. [2], and the probability of landing impact is equal to APX*APY in which APY is computed separately by Eq. 2.4, Ref. [2]. An example of computation is shown in Table 1.14B. The coefficients of APX and APY vary with aircraft weight, tire radius, navigation bandwidth and facility classifications. For instance, the figure .3640 means that one take-off operation of B747 aircraft on a runway with normal/visual navigation aid will result in a probability of 0.3640 that there will be a wheel load repetition on the same spot of a runway pavement.

Table 1.14A AIRCRAFT FILE

AIRCRAFT	CODE	MTOW MLG WHEEL WHEEL	MLRW WGT X-COORD Y-COORD	OEW PSI	RANGE FREQ	NWHEEL	XMAX
3	DC10/10	430000.	364000.	235000.	LONG		
		.4700	.1175	170.	1.1	8	474.
		0.	-54.	0.	-54.	366.	420.
		366.	420.				
		0.	0.	64.	64.	0.	0.
		64.	64.				
8	B727-200	172000.	150000.	97000.	MEDIUM		
		.4618	.2309	170.	1.6	4	259.
		0.	-34.	191.	225.		
		0.	0.	0.	0.		

Table 1.14B PROBABILITY DISTRIBUTION OF AIRCRAFT LOAD

AIRCRAFT	RADIUS TOW	RADIUS LRW	RADIUS TDW	APY
B747	7.5680	6.9540	8.5168	.2229-02
DC10/10	9.1435	8.5326	10.4503	.2734-02
L1011	8.4568	7.9731	9.7650	.2555-02

APX FOR BANDWIDTH NORM/VISUAL

AIRCRAFT	RW			TW		
	TOW	LRW	TDW	TOW	LRW	TDW
B747	.3640	.3344	.4096	.4168	.3830	.4690
DC10/10	.2348	.2191	.2684	.4463	.4165	.5101
L1011	.2181	.2056	.2518	.4207	.3967	.4858

1.5.c. PAVEMENT DAMAGE - DEFLECTION CRITERIA

The first set of equivalency analysis is based on the cummulative deformation of pavement due to the operation of aircraft. The theoretical and experimental background are given on pp. 58-63, Ref. [2]. The types of pavement for new construction and existing facilities have been simplified and documented in the computer default file. If more exact computation is required, the final pavement composition shall be used to over-ride the default system. With the inputs of aircraft weight, the surface deflection of pavement is computed by GELS (general equilibrium of layered system) and tabulated in array of aircraft type and operational weight for one specified model pavement. (see Table 1.15). Then Eqs. 2.20 and 2.21, Ref. [2], are used to compute the equivalency in conforming with conditions: (1) type of pavement, (2) selection of equivalency aircraft (3) ground navigation aid, (4) demand forecast, (5) service year and (6) facility location. With reference to the volume of aircraft operations, gear configuration and tire pressures, the most important aircraft operation is the B727 which is used in the computer program as the equivalency aircraft. The output of this program is an equivalent number of single type aircraft operation with respect to pavement surface deflection criteria AAND (see Table 1.16). The computer program is also designed to consider other aircraft for equivalency operation. An additional 10 to 20 minutes of CPU time are required for new computation.

Table 1.15 SURFACE DEFLECTION AND LAYER STRESS BY GELS

MODEL PAVEMENT:	CONC	PCC	12.0	4000000.	.15
		CTB	6.0	200000.	.25
		SSBS	8.0	10000.	.35
		SUB	INFI	7500.	.35

AIRCRAFT	SURFACE DEFLECTION, WZ			STRESS AT LAYER: PCC		
	TOW	LRW	TDW	TOW	LRW	TDW
B747	.16937	.14356	.21339	371.2	319.7	457.6
DC10/10	.12090	.10582	.15665	396.7	352.3	497.5
L1011	.10851	.10582	.14321	362.1	327.2	462.9
DC8(B707)	.10879	.08626	.12753	372.4	301.2	430.8
B727-200	.06683	.05978	.08764	383.1	345.1	491.9

1.5.d. PAVEMENT DAMAGE - STRESS CRITERIA

Similar to deflection criteria, the tensile stress in governing layer component is computed by GELS and tabulated in array (see Table 1.15). The equivalency is computed by Eq. 2.19, Ref. [2]. Because fewer transfer functions are used in stress analysis, the equivalency computation is rather simple. An example of output is given in Table 1.16. It can be seen that for one common set of aircraft operating on an identical pavement, the equivalent single type aircraft operation may be different with respect to progressive deformation and cummulative stress damage. This is a special finding of functional pavement design program.

Table 1.16 COMPUTED EQUIVALENT SINGLE TYPE AIRCRAFT OPERATION

EQ. AIRCRAFT: B727-200	CLASS: 3/CC	FACILITY:	RW 13L
BANDWIDTH: LIGHTS/ILS	FORECAST: FAMSUG	YEAR: 5	
STATIONS 0. TO 10.	LOCATION: KEEL		

	DEFLECTION CRITERIA			AND			AAND
	TOW	LRW	TDW	TOW	LRW	TDW	
B747	3.9E 00	3.1E 00	4.8E 00	0.0	0.0	0.0	
DC8(B707)	2.6E 00	1.5E 00	3.1E 00	7.7E 05	7.2E 04	0.0	
B727-200	1.0E 00	6.9E-01	1.8E 00	2.5E 03	6.7E 02	0.0	
B7N7-200	1.2E 00	8.0E-01	2.0E 00	4.3E 03	9.7E 02	0.0	
				7.8E 05	7.4E 04	0.0	8.5E 05

	STRESS CRITERIA			ANS			AANS
	TOW	LRW	TDW	TOW	LRW	TDW	
B747	4.7F-01	3.6E-02	1.5E 01	0.0	0.0	0.0	
DC8(B707)	1.4E 00	2.6E-02	9.1E 00	2.0E 04	3.2E 02	0.0	
B727-200	1.0E 00	1.5E-01	9.8E 01	2.5E 03	3.4E 02	0.0	
B7N7-200	3.8E 00	3.1E-01	2.8E 02	8.1E 03	6.1E 02	0.0	
				3.1E 04	1.3E 03	0.0	3.2E 04

1.6. PRESENT FUNCTIONAL LIFE OF EXISTING PAVEMENTS

The purpose of this subsystem is to evaluate the strength of existing pavements with respect to cumulative stress damage and progressive deformation of the pavement structure. The cumulative stress damage is an indicator of maintenance needs, STR/MT, while the progressive deformation represents the deterioration of pavement function, i.e., smoothness of pavement surface, DEF/DI. The flow chart is shown in Table 1.17.

Table 1.17 FLOW CHART OF PRESENT FUNCTIONAL LIFE

```
Default System     Job Inputs      Processing        Output Files
Computed Inputs                    Program

                   PFLPAV
                   Eq. Aircraft -> GELS/PFL          NDT Inventory File
                   Facility ID        |                    |
                                      |    +---------------+
                                      v    v
                                   Stress Deflection
System Default Values -----------> of PFLPAV
                                      |
                                      |                Equivalent Single
                                      |    +-----------Type of Aircraft
                                      |    |           AAND, AANS
                                      v    v
                               Anticipated Life
                               No. of Repetitions ---> Present Functional
                               ANDA, ANSA                   Life
```

1.6.a. FUNCTIONAL LIFE - DEFLECTION CRITERIA

The NDT inventory file and demand forecast of aircraft movement are used in computer analysis to determine the present functional life which indicates the pavement's ability to maintain structural stability over and above the deterioration under loading and enviromental factors. The functional service life of a pavement may be evaluated with respect to: (1) the riding quality of pavement surface, and (2) the need for maintenance. The riding quality of a pavement surface is governed by its wave spectrum as well as by the speed and landing gear characteristics of moving aircraft. Among the current operating aircraft fleet, B727-200 and DC-8-63 are the most sensitive aircraft with respect to vibration at speeds exceeding 100 knots. The amplitude of wave spectrum is directly related to the magnitude of cumulative damage, a term used in pavement engineering to indicate the change of pavement surface. This computer program will determine the anticipated number of load repetitions which will produce a cumulative pavement deformation based on the aircraft velocity, its dynamic response and E-value of the pavement support. The theoretical and experimental background of the computation is shown on pp. 58-64 and Eq. 2.22, Ref. [2]. The functional life of existing pavement is effected by ANDA which is the number of load repetitions that the equivalency aircraft will not vibrate in excess of the defined dynamic response DI at a crossing speed, V.

The first input for this subsystem is the existing pavement file which is retrieved from the input file for equivalency computation. The other input is the NDT inventory file which is the product of NDT3. The first processing program, GELS, determines the critical component stress and surface deflection. This information is stored as a computed input file. The next input, the system default values, is introduced in the second processing program to evaluate the pavement's capacity to withstand stress or deflection accumulation. The output is the anticipated functional life in load repetitions with respect to deflection criteria (ANDA). These outputs are stored in the file for further processing of present function life (PFL).

1.6.b. FUNCTIONAL LIFE - STRESS CRITERIA

Similar to deflection criteria, the functional life, ANSA, is computed by GELS, according to Eq. 2.17, Ref. [2]. The purpose of this computation is to indicate the need for maintaining the structural integrity of existing pavement. Theoretically, the beginning of maintenance needs coincides with the ANSA load repetition which suggests the possibility of formation of fine stress cracks. At the early stage of crack formation, the pavement surface retains its original riding quality and there is no detectable degradation on the functional performance of that pavement. As the environmental factors and stress concentration accelerate the propagation of pavement cracks, there is a definitive need to preserve the integrity of pavement structure either by local rehabilitation or system strengthening. The results of computer analyses indicate that pavement structure deteriorates many times faster if its base and subgrade are saturated.

Deterioration of many local pavements can be related to the penetration of surface water through joint/crack openings and, then, water accumulation in the subgrade and base. For preserving longer and better pavement performance, an extensive joint/crack sealing program should be considered for all pavements on the airport prior to the consideration of any pavement rehabilitation or strengthening program. In the output of this computer program, the functional life will be evaluated for existing pavements under either normal and/or wet base conditions.

1.6.c. DEFINING PRESENT FUNCTIONAL LIFE

In the final process, the traffic equivalency outputs AAND and AANS are retrieved from the computer data file and the one year traffic volume is used for analysis. The present functional life (PFL) is computed in terms of ANDA/AAND as "governed by DEF/DI", and ANSA/AANS as "governed by STR/MT". The PFL is expressed in years of anticipated functional life. Because of the nature of the demand forecast and the method of compution, any functional life greater than five years is simply expressed by >5.00 (see Table 1.18).

Table 1.18 SUMMARY OF PRESENT FUNCTIONAL LIFE

GOVERNED BY DEF/DI *						GOVERNED BY STR/MT #			
.12G NORM	.18G NORM	.25G NORM	.12G WET	.18G WET	.25G WET	.18G NORM	.30G NORM	.18G WET	.30G WET
>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
2.50	>5.00	>5.00	1.39	>5.00	>5.00	>5.00	>5.00	>5.00	2.46
0.31	>5.00	>5.00	0.19	3.78	>5.00	>5.00	4.03	0.00	0.00

* Dynamic response of aircraft. # Impact of aircraft.

1.7. UNIVERSAL MECHANISTIC ANALYSIS OF PAVEMENT STRUCTURE

The output of PFL indicates the anticipated functional life of each segment of existing pavements. Airport users are in a position to decide the need for new construction or rehabilitation of existing pavement in order to meet the functional requirements for aircraft operations. From the view point of engineering management, the new pavement and rehabilitation programs shall be designed to consider many design alternatives, to meet the user's requirements and to be economical and practical. These basic requirements reflect the apparent deficiencies of today's pavement design methods which are not governed by functional requirements or cost-benefit study but are based on policy decisions in selecting pavement materials for construction. In the functional design, a universal mechanistic design method which is programmed for computer analysis, is used in determining the pavement thickness for all types of construction materials. The flow diagram is shown in Table 1.19. The first input is the set of default pavements for equivalency computation of aircraft movement. The default pavements represemt the best estimate of pavement type required for new construction or reconstruction. The processing program, coded FAM, utilizes the same logic as discussed under the heading "Equivalent Single Type Aircraft Operation". The outputs of this subsystem consist of (1) ATM in 5, 10 and 20 year

service, and (2) AAND and AANS for effective load repetitions with respect to deflection and stress respectively.

Table 1.19 FLOW DIAGRAM OF UNIVERSAL ANALYSIS OF PAVEMENT STRUCTURE

Default System Computed Inputs	Job Inputs	Processing Program	Output Files

Default System for FAM → FAM → ATM, AAND, AANS

Pavement Model
PAVDES Commend
Keel & Sides ID

NDT Inventory File

System Default Values → Functional Requirements

↓

Limiting Criteria
Deflection and Stress

↓

Grid System for Design Charts ← GELS/HDES

Pavement Stress ←

Thickness of Iteration
Layer Governed by
DEF/DI or STR/MT

The next set of inputs consists of keel and side identification, command of pavement design, and instruction for design iteration of governing layer, ESUB grid and EPAV grid. The NDT inventory file is also retrieved as an input. The background for this processing program is discussed on pp. 59-62, Ref. [2]. The output of this computation program is shown in Table 1.20. The term "Limit DEF/WZ" indicates the limiting surface deflection of pavement and "Limiting Stress" indicates the limiting pavement stress of the governing component layer. The system is programmed to handle two pavement base drainage conditions (normal dry moist and wet saturated base) and, also, three traffic volumes (half, full and double the demand forecast). One set of design limits, DEF/WZ and stress, is shown in Table 1.20. The other five sets are similar but are stored in computer file.

Table 1.20 SUMMARY OF AIRCRAFT FORECAST AND FUNCTIONAL LIMITS

					FOR ESUB NORM AND FAM DEFINED			
FACILITY	STATION FROM-TO	LOC	ESUB NORM	ESUB WET	AANS	AAND	LIMIT DEF/WZ	LIMIT STRESS ASBS
RW TEST	0.- 20.	KEEL	9109.	5465.	94688.	681517.	0.0894	101.8
RW TEST	0.- 20.	SIDE	9109.	5465.	889.	6815.	0.2059	168.2

1.7.a. GENERAL EQUILIBRIUM THEORY

The universal mechanistic theory used in this computer program is general equilibrium of layered system (GELS) developed by Burmister in

1945, pp. 201-207, Ref. [1]. In today's pavement research, there is more production on special theories than the application of general theories. It means that theories developed for asphalt pavement are not supposed to be used for concrete pavement design or vise versa. From the view point of engineering mechamics, pp. 181-201, Ref. [1], the general equilibrium equations shall satisfy the conditions:

$\nabla^2\nabla^2\phi = 0$, in which ∇^2 is differential equation operator. The stress-strain condition on all boundaries are in equilibrium. Boussinesq assumed that $\phi = B(r^2 + z^2)^{\frac{1}{2}}$ for the solution of half space elastic system and Burmister advanced the solution for multi-layered system by assumming that $\phi = J_o(mr)(A + Bz)e^{mz} + (C + Dz)e^{-mz}$. The general equilibrium applies no limitation on the type of layer material as long as it is characterized by its stress-strain property.

In concrete pavement design, the commom approach is the use of well-known Westergaard theory for elastic plate on Winkler foundation, pp. 219-228, Ref. [1]. The basic equation is $\nabla^2\nabla^2\omega = p/D$. It means that the bending deformation is the only condition considered in equilibrium analysis. Shear and stress equilibrium are neglected. Moveover, the linear spring constant k-value used in the above equation in terms of p/D does not reflect the physical property of subgrade support. Except for pavement detail analysis, the theory for elastic plate on Winkler can not be used as a universal mechanistic design method.

1.7.b. DESIGN CHARTS FOR MANUAL OPERATION

The introduction of design charts by Pickett and Ray should be considered to be the major reason for the popularity of the Westergaard theory, pp. 228-231, Ref. [1]. There are many engineers who can design pavements easily with the aid of design charts. The Burmister's GELS theory is so complex and complicated in computation that there was no meaningful charts or coefficient tabulations for pavement design until the work by Jones in 1962 when the use of digital computer was in the early development stage. Since 1971, there have been two major computer programs available for the operation of GELS, pp. 211-212 and 254-255, Ref. [1]. For this functional pavement design, the GELS program has been reconstructed for multi-aircraft operation on various pavements. For the benefit of conventional design process, a group of 54 design charts have been plotted by computer for 27 types of pavement composition and four of these charts for common asphalt and concrete pavements are reproduced in PART THREE (see Figs 3.1, 3.2, 3.4 and 3.5).

1.7.c. SYSTEM ITERATION AND AUTOMATED DESIGN

The pavement thickness design by GELS has been automated in the computer program. The establishment of design limits will make it possible to iterate by GELS/HDES the thickness of pavement layer either for deflection or for stress criteria whichever determines the thicker pavement layer. For an average two-runway airport, this iteration requires from 200 to

400 minutes of CPU time. To expedite the design computation, the design charts discussed under the previous heading have been permanently stored in the computer file. The CPU time for current program has been reduced to about 4 to 8 minutes for the same set of thickness designs. An example of thickness outputs is shown in Table 1.21.

Table 1.21 SUMMARY OF THICKNESS ANALYSIS

			NHICKNESS OF PCC LAYER					
FACILITY	STATION FROM-TO	LOC	FAM NORM	FAM/2 NORM	FAM*2 NORM	FAM WET	FAM/2 WET	FAM*2 WET
RW 18REXT	90.-108.	KEEL	11.3	10.9	11.6	12.2	11.8	12.6
RW 18REXT	90.-108.	SIDE	7.1	6.8	7.4	7.9	7.6	8.2
APRN EAST	0.- 10.	KEEL	10.8	10.4	11.2	11.6	11.2	12.0

1.8. COST BENEFIT ANALYSIS

With the establishment of pavement thickness design shown in Table 1.21, the computer program prepares the cost information to aid airport management in formulating a fiscal policy for pavement construction and rehabilitation. A flow diagram of the computer operation and the details of the last subsystem, COBEN, are shown in Tables 1.22A and 1.22B.

Table 1.22A FLOW DIAGRAM OF COST BENEFIT ANALYSIS

```
Inputs                         Processing Program        Outputs

NDT Inventory File  ---------> FAM
User's Requirements            GELS/HDES
                                   |
                                   v
                               Functional Criteria ----> Thickness Design
                                   +----------------------------+
                                   v
Regional Cost Values --------> Cost Analysis ----------> Cost Benefit Study
```

Table 1.22B FLOW DIAGRAM OF SUBSYSTEM COBEN - COST ANALYSIS

```
Default System                          Processing
Computed Inputs      Job Inputs         Program          Output Files

ICC Pavement Components -----------------+
Default Cost Values                      |
                                         |
             Regional Cost Values --+    |    +-------- Thickness of Pavement
                                    v    v    v
Unit Price of Components ----> Cost Analysis 1 ----> Initial Construction Cost
                                         |
                                         v
Pavement Stress -------------> Cost Analysis 2 ----> Annual Maintenance Cost
                                         |
                                         v
Financial Cost Parameters ---> Cost Analysis 3 ----> Present Cash Value
                                         |
                                         v
                               Cost Analysis 4 ----> Cost Benefit Study
```

1.8.a. PAVEMENT COMPOSITION AND BENEFIT LISTING

The ultimate purpose of pavement evaluation is to develop a pavement composition which is economical, practical, and meets the specification of user's requirements. The process serves a dual function in optimizing pavement composition as well as in price-tagging the user's requirements. For objective evaluation, all designs are based on cost/benefit values. The cost/benefit listing for this pavement computer program will provide information on:

1. Selection of optimum pavement material.
2. Optimization of layer thickness and quality standard.
3. Length of service year.
4. Ground navigation system.
5. Demand forecast and aircraft operational weight.
6. Drainage of pavement base.
7. Surface smoothness requirements.
8. Subgrade variation and stabilization.
9. Construction practice and size of project.
10. Temperature effect on asphalt pavements.
11. Financial cost and long-range fiscal policy.
12. Down-time and airport traffic delay.

1.8.b. INVENTORY OF COST DATA

There are three sets of cost data which should be completed for the cost-benefit analysis.

1. The first set of cost data is regional cost values of construction materials and labor. If job cost data are not available, a set of default cost values shall be used in the computation. The default cost values were compiled for FAA regions based on construction data published in the current issues of Engineering News Record.
2. The second set of cost data is a default system compiled in the program to estimate the unit price of layer components in dollars per inch per square yard. The computation is very similar to contractor's cost estimate except the equipment cost is included in the cost of the skilled equipment operator.
3. The third set of cost data is for financial analysis which affects the cost of revenue bond and the discounted cash value. The default value of these cost data are shown in Table 1.23.

1.8.c. INITIAL CONSTRUCTION COST (ICC)

With the layer thickness output from GELS/HDES program, the initial construction cost can be estimated for each pavement design (see Table 1.24 under ICC). The processing program is basically an arithmetic multiplication and summation of cost elements. For example, the ICC for asphalt pavement of test runway is:

$$ICC = 2x1.30 + 22.5x1.19 + 6x0.56 + 0.38 = \$33.13/s.y.$$

Table 1.23 LISTING OF FINANCIAL, REGIONAL AND DEFAULT COST DATA

COST ELEMENTS OF PAVEMENT LAYER

LAYER	PCBT IWFAT	FIAGT RSWLB	COAGT LBBM	ASCLT CLHR	HLBT SLEHR	POZBT	SFST
1	.0	.0235	.0500	.0051	.0	.0	.0
	.0	.0	.0	.0112	.0217		
2	.0007	.0	.0200	.0	.0020	.0067	.0374
	.0	.0	.0	.0027	.0102		

REGIONAL COST VALUES

COST	CODE	DATE	ARM	ACE	AWE	AEA
1	PCBT	5/30/78	47.80	46.95	52.10	42.00
2	FIAGT	5/30/78	6.75	3.65	5.60	5.25
3	COAGT	5/30/78	7.15	3.65	5.60	6.20
4	ASCLT	5/30/78	72.50	80.00	64.00	81.00
5	HLBT	5/30/78	80.00	75.00	80.00	75.00
6	POZBT	5/30/78	5.00	3.50	25.00	4.00
7	SFST	5/30/78	3.00	2.50	3.50	3.50
8	IWFAT	5/30/78	2.00	2.00	2.50	2.50
9	RSWLB	5/30/78	.38	.37	.38	.37
10	LBBM	5/30/78	.61	.50	.45	.40
11	CLHR	5/30/78	8.17	11.20	12.20	12.22
12	SLEHR	5/30/78	10.40	14.15	15.13	14.65

FINANCIAL COST DATA

AIRB	ARCD	ASCCC	ASCMC	NBL	NSLP
.08	.10	.09	.02	30.	20.

1.8.d. ANNUAL MAINTENANCE COST (AMC)

At the end of pavement thickness design, a list of critical layer stress will be temporarily stored in the computer file. The processing program, Cost Analysis 2, p. 79, Ref. [2], yields an estimate of annual maintenance cost, AMC as shown in Table 1.24. Because maintenance costs are applicable during the entire life span of a pavement, it is desirable to convert all cost estimates into present cash values (PCV) which will reflect the financial cost parameters as stored in the default system. Adjustment on these cost parameters can be made by job inputs. The computation background of this processing program, Cost Analysis 3, is given on pp. 80-81, Ref. [2]. The output is present cash value, PCV as shown in Table 1.24.

1.8.e. WEIGHTED PRESENT CASH VALUE

The final processing program, Cost Analysis 4, estimates the weighted average of present cash value for each facility. The computation formulas are given on p. 82, Ref. [2]. The final output is the weighted average PCV in dollars per square yard of runway or taxiway in full width (see Table 1.25). There are ten design alternatives of equal performance for

identical user's requirements. With this background, the airport management will be in an advantageous position to reach a sound fiscal policy on the airport pavement program.

Table 1.24 LISTING OF PAVEMENT DESIGN AND COST ANALYSIS

EQUIVALENT AIRCRAFT OPERATION: B727-200

PAVEMENT MODEL:	CODE	LAYER	THICKNESS	E-VALUE	POISSON	UNIT-PRICE
	AC	ASTOP	2.0	200000.	0.23	1.30
		ASBS	****	150000.	0.24	1.19
		AGBS	6.0	40000.	0.28	0.56
		SUB	INFI	++++	0.34	0.38

FACILITY	DESIGN SERVICE YEARS	FUNCTION GOVERNED	AMC	ICC	PCV	THICKNESS ****
RW TEST	20	DEF/DI	0.11	33.13	34.04	22.5
RW TEST	20	DEF/DI	0.11	39.63	40.31	28.0
RW TEST	20	STR/MT	0.12	7.82	9.76	1.2
RW TEST	20	STR/MT	0.12	10.20	12.05	3.2

Table 1.25 COST/BENEFIT STUDY

	WEIGHTED AVERAGE OF PRESENT CASH VALUE, $/SY						
FACILITY KEEL:	LCF	AC	CC	CCL	LC/PAV	AC/PAV	CC/PAV
SIDE:	LCF	AC	CC	CCL	LC/PAV	AC/PAV	CC/PAV
APRN INT :	13.63	12.69	20.90	19.73	9.78	5.82	15.32
APRN EAST :	14.19	14.40	22.02	20.33	10.67	8.24	16.89
RW TEST :	13.47	16.32	20.59	19.76	10.58	8.69	16.44
RW TEST :	13.87	18.18	21.83	20.31	12.15	10.69	18.14

1.9. STRUCTURAL DESIGN OF PAVEMENT DETAILS

The outputs of computer program PAVBEN provide airport users and engineer/management a general design evaluation and cost-benefit analysis for all types of airfield pavement which can be used as background reference in formulating an appropriate fiscal policy. After this decision, one or two desirable types of pavement are normally selected for final design. The pavement composition, layer thickness, material characteristics and construction features will be carefully re-studied. All default values will be re-evaluated and a set of valid job inputs will be developed for the final design. The use of GELS, default values in COBEN and thickness analysis of default pavement system can be considered as a preliminary engineering study, while structural details will be developed at the final stage of pavement design. The computation flow is rather simple in comparision with the main program. However, the computer command requires

manual control in separate computation processes. Because the final design depends largely on the prescribed details of airport operation, the fiscal policy of management and engineer's judgment, no universal computer program is applicable for the final design. For instance, the physical properties of asphalt and portland cement concrete are significantly different. Structural details of such layer should be tailored for its performance. Detailed discussions will be given in the following articles.

1.9.a. VERTICAL DISCONTINUITY - CRACKS AND JOINTS

The most common feature of high strength paving material is volumetric change due to environmental fluctuation of moisture and temperature. There are designed joints and natural cracks to compensate for such volumetric movement. The presence of pavement cracks has no serious effect on aircraft movement as long as the cracks are properly sealed and the pavement surface is smooth and clean. However, joints or cracks represent vertical discontinuities which are assumed not to exist in layered elastic theory used as the base for GELS.

For pavements at Newark, JFK, Zurich and Portland International airports, adequate base layers are provided. With a deep stabilized base, the temperature or moisture fluctuation will have less effect on the stress and deflection of surface layer than without stabilized base. At Newark, construction joints are spaced 200 ft apart in both directions. In the last 10 years, no deep crack was observed in the heavy pavement structure, having stabilized base more than 18 inches in thickness, except hairline cracks were observed on asphalt wearing surface at a spacing ranging from 25 to 50 ft apart. For stabilized base less than 12 inches in the shoulder area, the crack spacing is about 15 ft. For many concrete pavements, the stability problems are usually in the base. The stress analysis of concrete top course seems to be over-emphasized in conventional pavement design.

In the future computer program for concrete pavement design, the final analysis will consist of two subsystems:

1. GELS will be used to design the concrete pavement base to meet the equilibrium of subgrade.
2. A finite element method will be used to design the concrete slab with defined vertical discontinuity. The Saxena's program, pp.233-236 and 256-272, Ref.[1], for plate on half space elastic foundation will be modified to satisfy the finite element method of elastic plate.

1.9.b. HORIZONTAL DISCONTINUITY - CAVITIES AND POCKETS

The condition under this heading also represents the fallacy of using elastic plate theory in pavement design which neglects the equilibrium of support system. With a high strength layer on unconsolidated base, such as concrete slab on aggregate base, there will be excessive permanent deformation in the base and subgrade support and, therefore, a cavity or pocket will be encountered under the concrete slab. Under repetition

of wheel loading, the slab has to deform as an unsupported plate prior to the development of subgrade support. Locked-in stress is developed which was not considered in the original plate analysis. Consequently, cracking of concrete slab is propagated.

The finite element computer program which is surposed to analyze vertical discontinuity, can be extended to evaluate the effect of horizontal discontinuity if a beam theory is introduced to compute the lock-in stress due to the presence of horizontal cavities. The expanded program will be able to analyze stress at dowels and reinforcing bars. In practical design process, GELS program can be used to evaluate the general equilibrium, structural composition and cost/benefit aspects of a pavement system. The finite element method will be utilized to check the stress-strain condition of pavement details. The integration of GELS and FEM programs will provide a complete operational model to analyze the global and local condition of a pavement system.

1.9.c. TRACTION OF TIRES

The tractive force developed from the aircraft tire is equal to the normal load times the coefficient of friction between tire and pavement. The maximum tractive resistence of pavement is equal to the horizontal stability of wearing surface including its bonding strength to supporting layer. If the horizontal resistence of wearing surface is less than tire's tractive force, a local failure on the pavement wearing surface will result. The design for traction of pavement surface is given on pp. 159-171, Ref. [1]. In future computer program, the finite element method will be used to evaluate the need of bonding strength between the wearing surface and its support system.

1.10. OPTIMIZATION OF PAVEMENT COMPOSITION

In the analysis for final design, GELS program will be used in optimizing the layer thickness and material property of layer components. The pavement program used for general thickness design and cost benefit analysis is still valid, except that many default values will be tailored for the pavement materials and practical construction conditions.

1.10.a. TIME-TEMPERATURE EFFECT ON MATERIAL CHARACTERISTICS

Soft subgrades and plastic materials have a time-dependent physical property. GELS program is not able to handle such a problem directly. In PART THREE, Material Characterization, all physical tests will be related to load frequency which is a time-dependent physical test. By selecting a time-related E-value, the GELS program may provide a better design output. Another concern is the temperature dependent physical property of asphaltic materials. For airports north of 37° parallel, the daily temperature variation can be as much as 40°F; seasonal fluctuation of 120°F; and the annual mean temperature is about 50°F. For airports south of 37° parallel, the annual mean temperature may be in the range of 70°F and 90°F. The

E-value of asphaltic layers used in GELS computer program are reclassified according to area mean temperature which will reflect the regional performance of asphalt pavements.

Layer	E-values, psi	Mean Temperature	Remarks
ASTOP5	200000.	50°F	Default Value
ASTOP7	100000.	70°F	
ASTOP9	50000.	90°F	
ASBS5	150000.	50°F	Default Value
ASBS7	85000.	70°F	
ASBS9	45000.	90°F	

1.10.b. SELECTION OF LAYER THICKNESS AND COMPOSITION

The GELS program provides a good framework for final pavement selection. For general reference, the following thickness and E-value ranges can be considered:

Pavement Material	Layer Thickness	Layer E-Value, psi
Concrete, portland cement	8 to 14 inches	2.5 to 5. millions
Asphalt Concrete	4 to 16 inches	40000. to 400000.
Rolled Lean Concrete Base	6 to 10 inches	1.0 to 2. millions
Stabilized Base in layers	6 to 30 inches	50000. to 1000000.
Aggregate Base	6 to 18 inches	20000. to 60000.

Within the ranges, an economical pavement composition can be designed by using GELS.

PART TWO SUMMARY OF NDT VALIDATION AT CIVIL AIRPORTS

During the NDT validation period, 1300 tests were conducted at Burlington, Denver, Los Angeles and Tampa Airports. (Tests at KCI were completed one year earlier.) All tests were conducted by WES under a uniform procedure which was established for the validation airports. The large volume of test data was processed by computer in the form of NDT inventory file for each airport. Based on the user's input on current aircraft movement (see Table 2.1) and the operational weights (see Table 2.2), the computer also processed the present functional life of the pavements at each airport. Brief analysis of outputs are presented in Article 2.1. The effect of existing pavements on NDT data was also evaluated. The results are outlined in the subsequent Article 2.3.

Table 2.1. AVERAGE DAILY AIRCRAFT MOVEMENTS - PEAK MONTH, 1977-1978

Aircraft	BTV	DEN	KCI	LAX	TPA
B747		2.		16.	
DC10/30				2.	
DC10/10		52.		38.	11.
L1011			4.	20.	14.
DC8(B707)	0.1	9.	14.	77.	10.
B720					
B727-200		260.	46.	90.	130.
B727-100			32.	70.	50.
DC9(B737)	19.	228.	42.	50.	69.
F27	10.	27.	19.	4.	
A300B4					*

*Operation of Air Bus was not known at the time of NDT evaluation.

Table 2.2. OPERATIONAL AIRCRAFT WEIGHTS IN THOUSAND POUNDS USED FOR PFL STUDY

Aircraft	BTV	DEN	KCI	LAX	TPA
B747		615.		615.	
DC10/30				515.	
DC10/10		390.		390.	390.
L1011			390.	390.	390.
DC8(B707)	280.	325.	325.	325.	325.
B720					
B727-200		157.	170.	170.	170.
B727-100			150.	150.	150.
DC9(B737)	85.	100.	100.	100.	100.
F27	40.	40.	50.	50.	

NOTE: For the effect of operational aircraft weight, see Part 2 of Ref. [2].

2.1 BRIEF DESCRIPTION OF NDT RESULTS

The computer printouts for NDT INVENTORY FILE and PRESENT FUNCTIONAL LIFE for each of the validation airports are shown in Appendix 2. A brief appraisal of the pavements, based mainly on the printout results, is given for each airport.

BURLINGTON Except two hard stands and portion of runway overlay, all airport pavements are very uniform and consist of three-inch AC on aggregate base which has been the standard asphalt pavement in the pre-1960's FAA advisory circular. The EPAV varies from approximately 22,000 to 36,000 psi and the corresponding ESUB ranges from 10,000 to 20,000 psi. The present functional life can be briefly outlined as follows:

1. Aircraft operation on runway may experience some vibration at low intensity;
2. Riding conditions on other pavements are satisfactory;
3. Pavement cracks may develop if the base is wet;
4. Apron pavements seem to have low ESUB.

DENVER More than ten types of pavement were observed during NDT. Consequently, the dynamic response measured by NDT reflect the conglomerate of pavement construction. The following ranges of E-values have been recorded:

12" Concrete Pavements	56,000 to 172,000 psi
9" Asphalt Pavements	45,000 to 125,000
16" Asphalt Pavments	63,000 to 143,000
Apron Pavements	35,000 to 61,000
North-South Runways & Taxiways	110,000 to 190,000
East-West Runways & Taxiways	46,000 to 125,000

At several locations, the computed ESUB is greater than 40,000 psi, which is unusually high for the soil condition. It is possible that some local asphalt overlays (patching) were not recorded on the drawings available during the NDT planning. According to the output of present functional life, all new pavements for north-south runways and related taxiways are well constructed and should have a satisfactory operation performance if the pavement base is properly protected from the penetration of surface water. For older pavements, the weak areas are: (1) cross taxiways from apron to east-west runways; (2) apron pavements are operational but require frequent maintenance; and (3) east-west runways which may have some problems regarding riding quality and structural cracks.

KANSAS CITY The pavement construction history indicates an orderly development of a modern airport. Older pavements were constructed in the 1960's and the earlier FAA design standards were used. The present functional life of all pavements are satisfactory except for three aspects: (1) the surface drainage is not adequate in some pavement area where pavement base is wet and NDT E-value is low; (2) older pavements, such as Runway 9L-27R, Taxiways C and D are relatively weak to accommodate today's aircraft operation; and (3) there are high traffic movements on taxiway B and, therefore, low NDT E-values (extensive cracks) have been recorded.

LOS ANGELES All pavement constructions were properly engineered and

maintenance is being guided by the airport engineers. Older pavements are of 12-inch concrete while the newer pavements are of 15-inch concrete. The maintenance program of Runway 25R and others, as indicated during the NDT, is effective and economical. Results of PFL for Runway 25R, from station 5 to 74 indicate that: (1) concrete pavement normally provide a smooth riding surface, and (2) the presence of pavement cracks will not affect the smooth operation of aircraft if the joints and cracks are properly maintained (i.e., repaired and sealed).

TAMPA Fast airport growth is noted by the construction history of the airport. High pavement strengths are recorded at terminal aprons, two north-south runways, and taxiways H and J. Other pavements are of older construction and follow the pre-1960's FAA standards. Except for the taxiway J Bridge, all new pavement constructions are properly and economically designed for smooth operation and structural integrity. If the pavement joints are properly maintained to prevent the intrusion of surface water, a long service can be expected for these pavements.

2.2. ANALYSIS OF NDT DATA

The correlation of NDT data with plate load tests are given in Ref. [2]. The effect of environmental conditions, airport operation and loading history of subgrade have been tested during the NDT validation program and will be outlined herein.

2.2.a. GEOLOGY OF SUBGRADE

During the NDT at airports prior to the validation program, there were indications that the geological condition of the subgrade has some influence on the strength of airport pavement. Therefore, in selecting the airports for the NDT validation program, the geological condition at the airport site was one of the major considerations:

In Fig. 2.1, the geological conditions are:

Burlington, Vt.	Ground Moraine
Denver, Co.	Residual Deposit
Tampa, Fl.	Coastal Sediments

The morainal deposit was subjected to the weight of the glacier which may contribute to the higher pavement strength at BTV. In Fig. 2.2, the subgrade conditions are:

Cleveland, Oh.	Glacial Deposit
New Orleans, Lo.	Delta Deposit
San Diego, Ca.	Land Reclamation

There is no indication at these three airports that the geological origin of subgrade soil has a significant effect on the strength of pavement.

The results shown in Figures 2.1 and 2.2 are for concrete pavement of both new and old construction. Similar results are shown for asphalt pavements (see Fig. 2.3). The soil condition at Los Angeles International Airport is predominantely of coastal dune sand deposit which turns to sandy silt on the east side of the airport. There is no indication that geological conditions have significant influence on the pavement performance.

2.2.b. REGIONAL CLIMATE

The regional climate discussed herein, will refer to the effect of temperature and moisture on the supporting strength of existing pavements. During the NDT validation, attempts have been made to demonstrate the significances of these factors.

REGIONAL TEMPERATURE In Ref. [2], it has been observed that E-value by frequency sweep NDT is practically independent of temperature fluctuation. In the selection of validation airports, the climate variation is also one of the major considerations. From the result of more than 1,600 tests, there is no indications that normal temperature fluctuation affects the reliability of NDT data acquisition. Typical NDT plots are shown in Fig. 2.4.

FROZEN GROUND The effect of temperature below freezing point is complicated by the presence of moisture in the pavement components as well as in the subgrade soil. For well-drained subgrade with no surface water penetration, the freezing temperature has little effect on pavement strength such as the 17-inch concrete pavement at BTV (see test 32 on Fig. 2.5). For pavements subject to accumulation of water and long period of freezing temperatures which causes deep frozen ground, the increase of pavement strength may be several times greater than its original capacity (see test 13 on Fig. 2.5). During the material tests by Majidzadeh, the dynamic E-value of frozen subgrade soil was up to 47,000 psi. By using GELS program, the depth of frozen ground is estimated to be 50 inches on February 3, 1978.

REGIONAL MOISTURE The accumulation of moisture in the base and subgrade is known to have a deleterious effect on the strength of pavement system. During the NDT validation program, attempts were made to compare the pavements in dry regions, such as LAX, with those in wet regions, such as TPA. A typical set of NDT data is plotted in Fig. 2.6. If a airport drainage system is properly designed and pavement joints and cracks are maintained, the regional moisture has no significant effect on the strength of airport pavements.

RAIN STORM Similar to regional moisture, the effect of rain storm was observed during NDT validation. The results are plotted on Fig. 2.7. At TPA, the concrete pavement joints and cracks are sealed. There seems to be no significant penetration of runoff during rain storm. On the other hand, the original runway (concrete) pavements at New Orleans which were about 15 years old and had random crackings, have been overlaid with asphalt. The effect of rain storm tends to reduce the pavement strength. A good airport drainage design together with a proper maintenance program will prolong the service life of existing pavements.

2.2.c. AIRPORT OPERATION

The aircraft movement and frequency of pavement maintenance will have a significant effect on the performance of existing pavements.

AIRCRAFT MOVEMENT The increase in aircraft movements can compact

the subgrade soil and, therefore, increase the load carrying capacity of the existing pavement. The side effects of subgrade consolidation will not be discussed at this moment. In Fig. 2.8, two sets of runway NDT data are plotted. For pavements in the touch-down zone, where take-off and landing traffic are concentrated, the pavement strength is about 50% stronger than those in the mid-portion of runway. The percent of increase applies to both concrete and asphalt pavement construction. This suggests that the strength gains can occur and may be found in the subgrade soil.

PAVEMENT MAINTENANCE Adequate pavement maintenace will prevent the penetration of surface water into base, subbase and subgrade and, therefore, will prevent rapid deterioration of pavement strength. The best example is R/W 25R pavement at LAX. Because the present service life of that pavement has been stretched beyond its original design plan, extensive stress cracks are encountered on the 12-inch concrete pavement. An intensive maintenance program has been carried out to seal all cracks and joints. The NDT strength of LAX pavement is as good as the newer pavement at KCI where a normal maintenance program is in practice (see Fig. 2.9). An advantage of LAX is that it is located in a better environment than KCI, i.e., less rainfall and no freeze-thaw problem.

2.3. TYPES OF EXISTING PAVEMENT TESTED

Under the validation program, attempts have been made to correlate NDT data with the composition of existing pavements. The correlation depended on the accuracy of as-built construction documents as well as the accuracy of available core boring records. In reviewing the construction records of these validation airports, the history of existing pavements was related to applicable prior design standards sponsored by the Army Engineers, CAA and currently by FAA. Prior to the mid 1960's, the pavement design was fairly uniform. Since the introduction of B727, and coincidentally the introduction of functional pavement design for Newark and JFK Airports, a variety of pavement constructions has been used. For the purpose of establishing a uniform validation program and expediting the practical application of present functional life analysis, the existing pavements are currently categorized into twenty present functional life pavements, PFLPAV. The major layer composition is shown in the second column of Table 2.3. The uniform PFLPAV categories were started in 1976 for NDT pavement evaluation at Cleveland Hopkins International Airport which was evaluated prior to the validation program. Since then and up to November, 1978, six airports including the validation airports have been evaluated by the same process. The range of E-value from NDT for most PFLPAV is summarized in Table 2.3.

TESTS ON CONCRETE PAVEMENTS Many runway pavements at major hub airports are of portland cement concrete construction. Prior to the early 1940's, the thickness of concrete pavement ranged from 8 to 10 inches. Thickened edge slab design was borrowed from highway construction. In the 1950's, the most common pavement thickness was 12 inches. Many of the 12 inch pavements are still in service at major hub airports, such as JFK and LAX. However, the maintenance of these pavements becomes increasingly difficult with time. Since the introduction of stabilized base for large scale pavement construction at Newark Airport in 1967, cement treated

base, asphalt stabilized base or econo-crete have been specified for many concrete pavement projects at airports. The thickness of conventional concrete pavements ranged from 14 to 17 inches at many airports and up to 22 inches in special case. The design curves shown in the early version of AC 150/5320 were practically inoperational. For the current NDT validation program, the thickness of concrete pavements ranged from 10 to 17 inches. A wide variation of pavement strength has been recorded. In order to show the general relationship between the pavement thickness and its strength, a common subgrade condition was used for the study. The NDT data of four concrete pavements at Denver Stapleton International are shown in Fig. 2.10 as an example of the relationship between concrete thickness and pavement E-value. For the example, the pavement E-value is proportional to the 2.6 power of concrete thickness.

TESTS ON CONCRETE OVERLAYS Concrete overlays on existing concrete pavement are not a popular strengthening scheme at hub airports. The major concern is whether to bond or not to bond the overlay to the existing pavement. In Fig. 2.11, the NDT data for an overlay pavement can be compared with that of a similar pavement prior to overlay. The pavement with 6" concrete overlay is about 23% stronger in E-value strength than a similar original 12" concrete pavement. According to AC 150/5320, if the layers are unbonded, the strength of overlay pavement is proportional to the summation of the squares of layer thickness. For the example shown in Fig. 2.11, the FAA concept is valid. The airport management should be made aware that the overlay layer is not bonded to the existing concrete pavement.

TESTS ON ASPHALT PAVEMENTS In the last twenty-five years, there has been increasing use of asphalt pavements at hub airports. The result is attributed to the introduction of CBR design curves in the early 1950's. The early asphalt airport pavement required 3" bituminous layer on compacted aggregate base for 5000 coverages of aircraft movement which was not mentioned in the early version of FAA Advisory Circular. Some of these pavements experienced rutting, shoving and cracking under repetitive loadings and leveling courses were added to upgrade the performance. In Fig. 2.12, the NDT data of asphalt pavement with six thickness are shown. The increase of pavement E-value, for this example, is proportional to the 1.35 power of asphalt layer thickness.

TESTS ON ASPHALT OVERLAYS Asphalt overlay is a popular pavement strengthening method at many civil airports. The existing pavements can be asphalt or concrete. Because of the bond between asphalt layers, all asphalt overlays have been treated as integrated asphalt pavement. For asphalt overlay on concrete pavement, reasonable bond between the layers can be anticipated if the concrete surface is properly prepared. In Fig. 2.13, the NDT data of three asphalt overlay pavements are shown. A concrete pavement without overlay is also shown. With four inch asphalt overlay, the pavement strength is more than doubled. Based on the NDT experience, the best pavement strengthening method appears to be asphalt overlay on concrete pavement. It increases the effective thickness of concrete layer in bending and reduces the opportunity for water penetration through concrete joints into base and subgrade, thus retaining the support capacity of the pavement system.

Table 2.3. RANGE OF NDT E-VALUES TESTED AT SEVEN CIVIL AIRPORTS

PFLPAV	LAYERS	BTV FALL	BTV WINTER	LAX	TPA	DEN	KCI	CLE	SAN
1/AC1	3" AC	21726	97329	22386	30425			16507	34101
		36791	205471	44226	38075				
2/AC2	6" AC	34885	129895	45099	29070	85414			20113
					52706				31445
3/AC3	9" AC				35221	45378		31951	63975
						115721		33014	
4/AC4	12" AC					71404			67664
						95223			
5/AC5	16" AC					62867		45157	69495
						125123		62683	
6/AC6	20" AC					143503			
8/CC2	10" PCC			67533					
				87483				43761	51748
9/CC3	12" PCC			36494	35394	56320	57909	60147	56542
				98402	92403	158051	107356	132565	98326
10/CC4	14" PCC						72382		
						103808	101383		
11/CC5	15" PCC			65726		108531			134770
				117445		155871			168903
12/CC6	16" PCC			88667	114323				
				126958	135392				
13/CC7	17" PCC	179545	158406			119665			
		165589	173233			189795			
14/OC1	4" AC	29191	120400		27139	35660			
	8" PCC				39996	67164	62416		
15/OC2	4" AC				42647			63232	
	10" PCC							126601	
16/OC3	4" AC							169956	81332
	12" PCC								136700
17/OC4	6" AC				79975	73543			
	10" PCC								
18/OC5	6" AC						83125		
	12" PCC						100078		
20/OC7	6" PCC				77622				
	12" PCC				117534				
0/SUB		10667			9141			12777	15155

TESTS ON AIRPORT BRIDGES Airport bridges such as the taxiway overpass at JFK and Sepulveda Tunnel under Runway 25R at LAX were designed by structure engineers with reference to the standard highway bridge specifications. Since the construction of overwater runway structure at LGA, several airport bridges have been constructed or strengthened, such as the taxiway J Bridge at TPA and I-70 Bridge at DEN. Because no standard specifications have been issued by FAA, the design requirements of airport bridges are not uniform. During the NDT validation, six bridge structures were tested (four at DEN and one each at TPA and LAX). The ranges of dynamic response of each bridge are shown in Figs. 2.14 to 2.17. It can be seen that the higher the E-value, the less the deflection of the bridge. The common interpretation is that the less deflection means the more rigidity or stronger the bridge structure. In Fig. 2.18, a comparison of the mid-span deflection is plotted for three airport bridges at TPA, DEN and LAX. The Sepulveda Tunnel at LAX has been in service more than twenty years but it is about 250% stronger than the Taxiway J Bridge at TPA. Currently, there is a load limitation on the Sepulveda Tunnel while the Taxiway J Bridge is open to all traffic. Based on the magnitude of structural deflection, Taxiway J Bridge may be susceptible to vibration during aircraft movement. Similar to the strength variation of airport bridges, the airport pavements also demonstrate a wide range of strength fluctuation. In Fig. 2.19, the NDT data of two bridges and the approach runway pavements are plotted. At DEN, the runway pavement is about three times stronger than its adjacent bridge structure over I-70. The strength of Sepulveda Tunnel is about 50% better than its approach runway pavements. There is no load limitation on I-70 bridge at DEN. From the view point of NDT evaluation, some guidance should be provided either by FAA or by the engineering profession on the airport bridge design and management of operation.

NDT PLOT

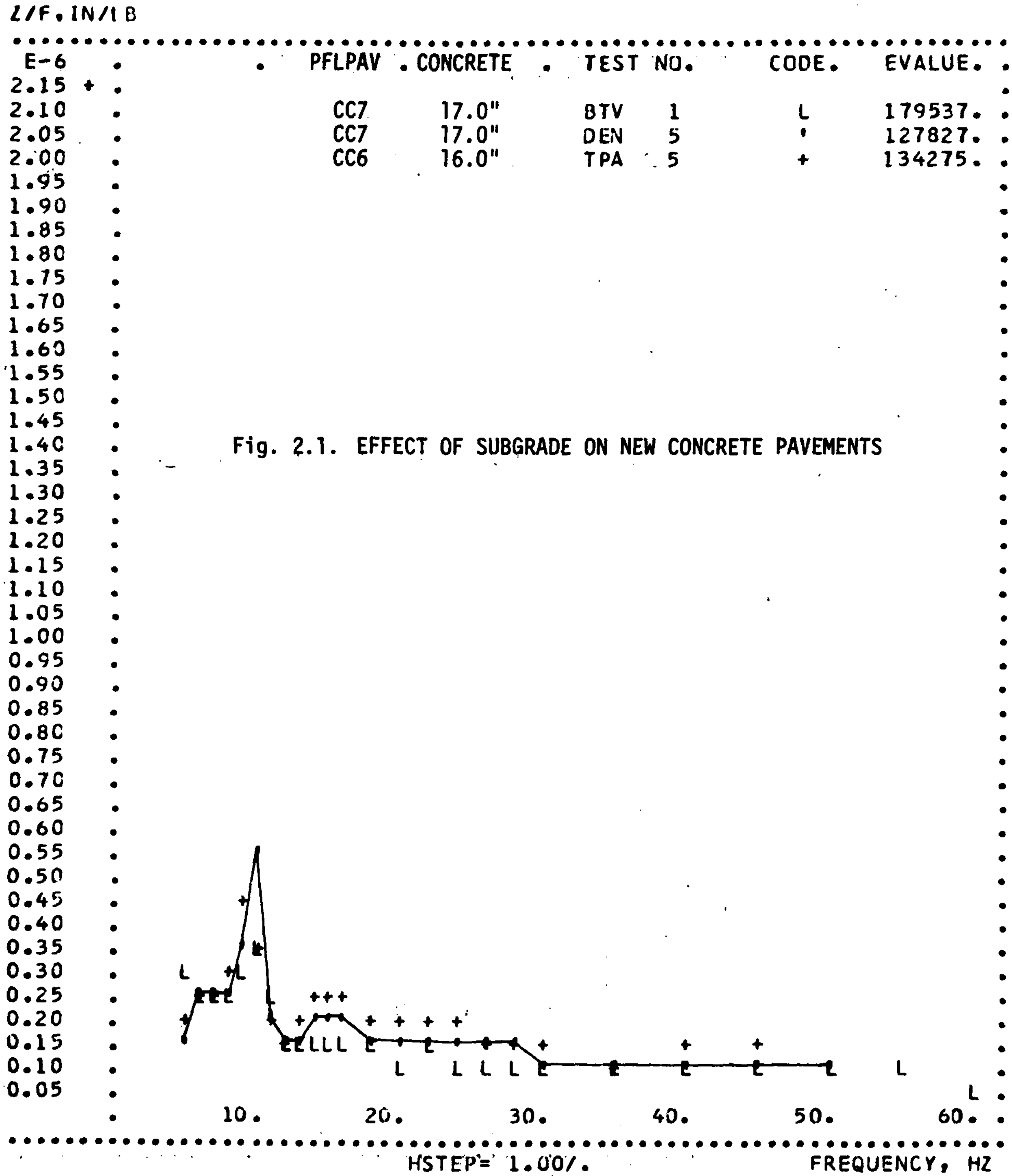

Fig. 2.1. EFFECT OF SUBGRADE ON NEW CONCRETE PAVEMENTS

NDT PLOT

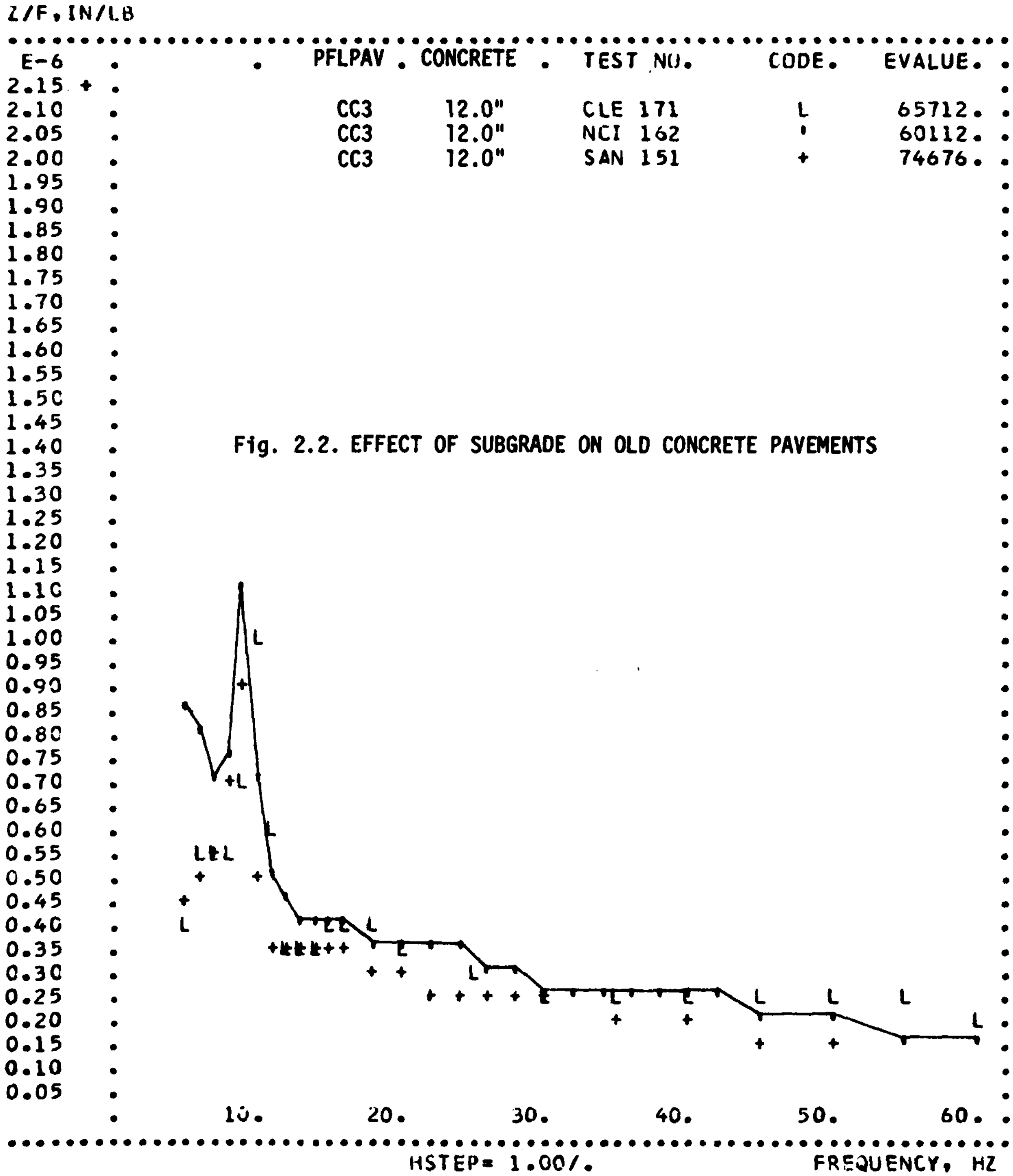

Fig. 2.2. EFFECT OF SUBGRADE ON OLD CONCRETE PAVEMENTS

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NDT PLOT

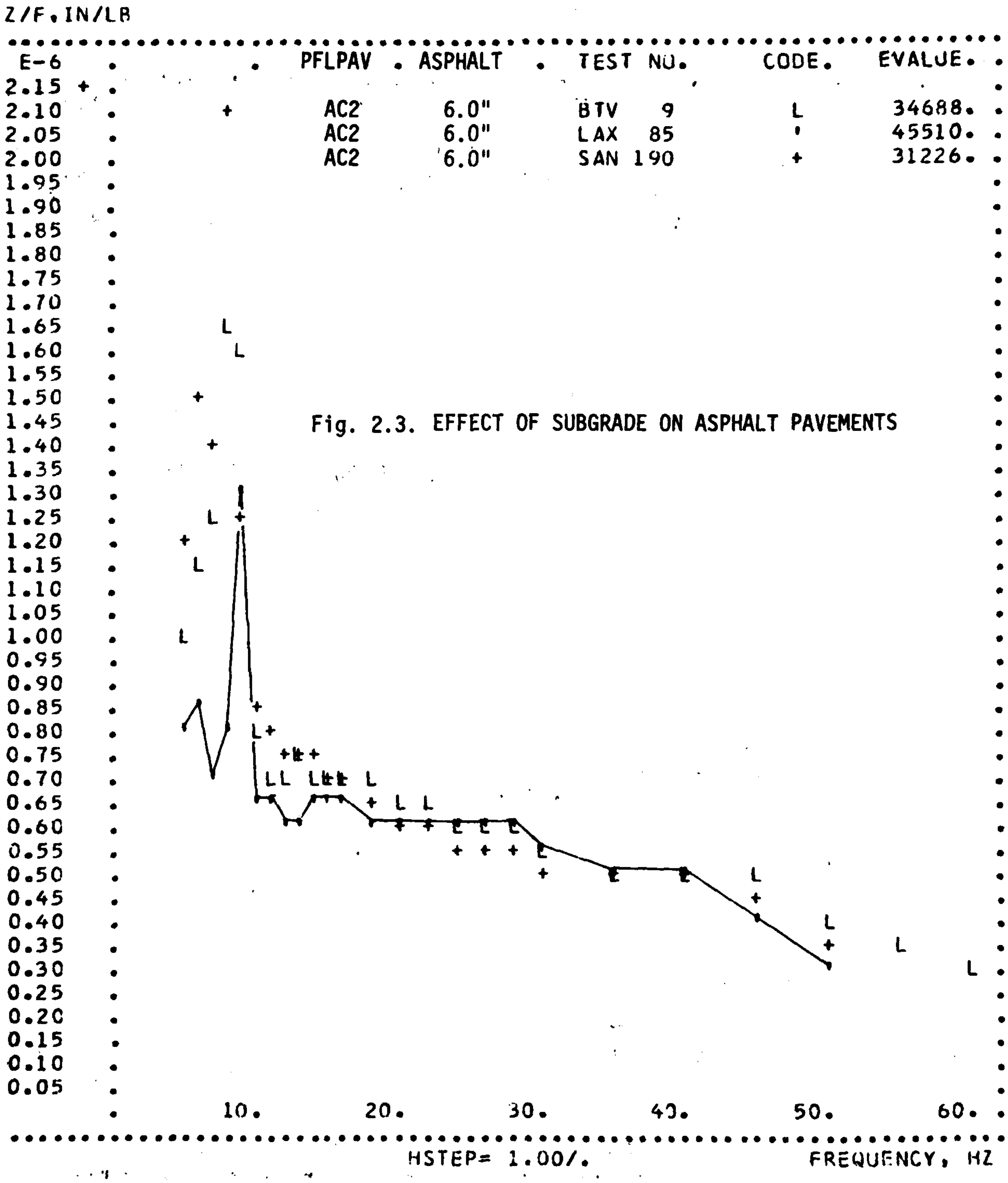

Fig. 2.3. EFFECT OF SUBGRADE ON ASPHALT PAVEMENTS

NDT PLOT

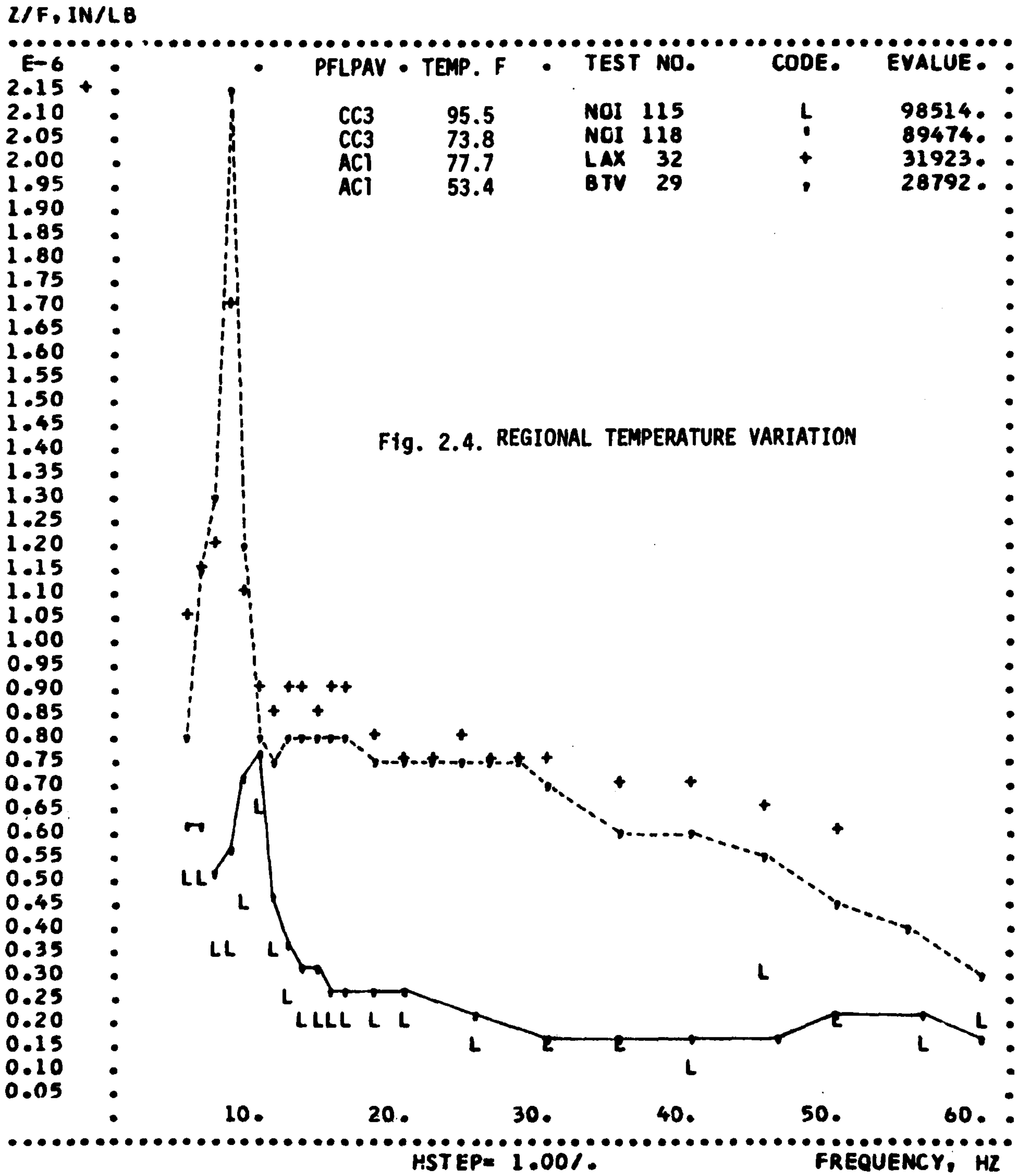

Fig. 2.4. REGIONAL TEMPERATURE VARIATION

NDT PLOT

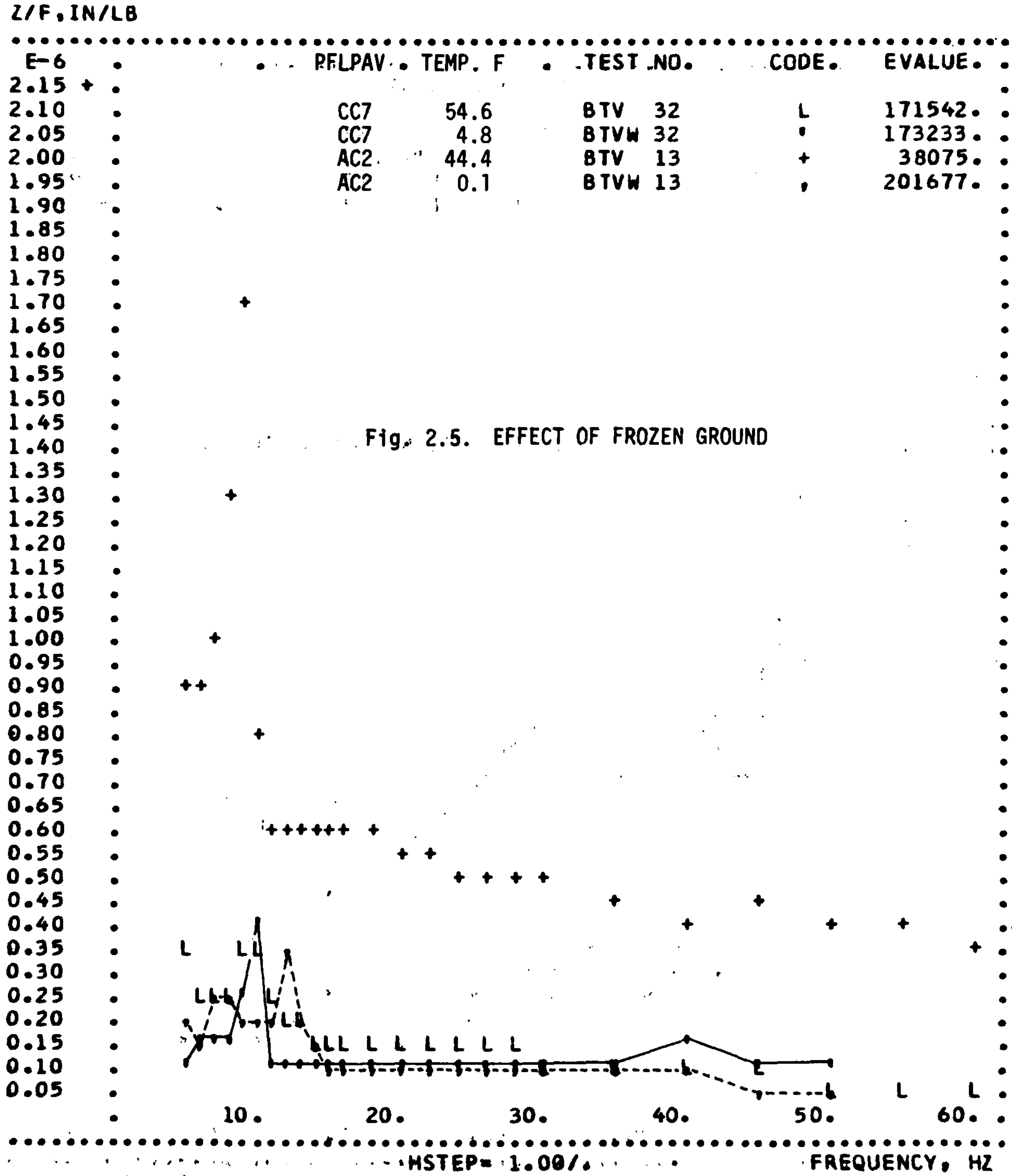

Fig. 2.5. EFFECT OF FROZEN GROUND

NOT PLOT

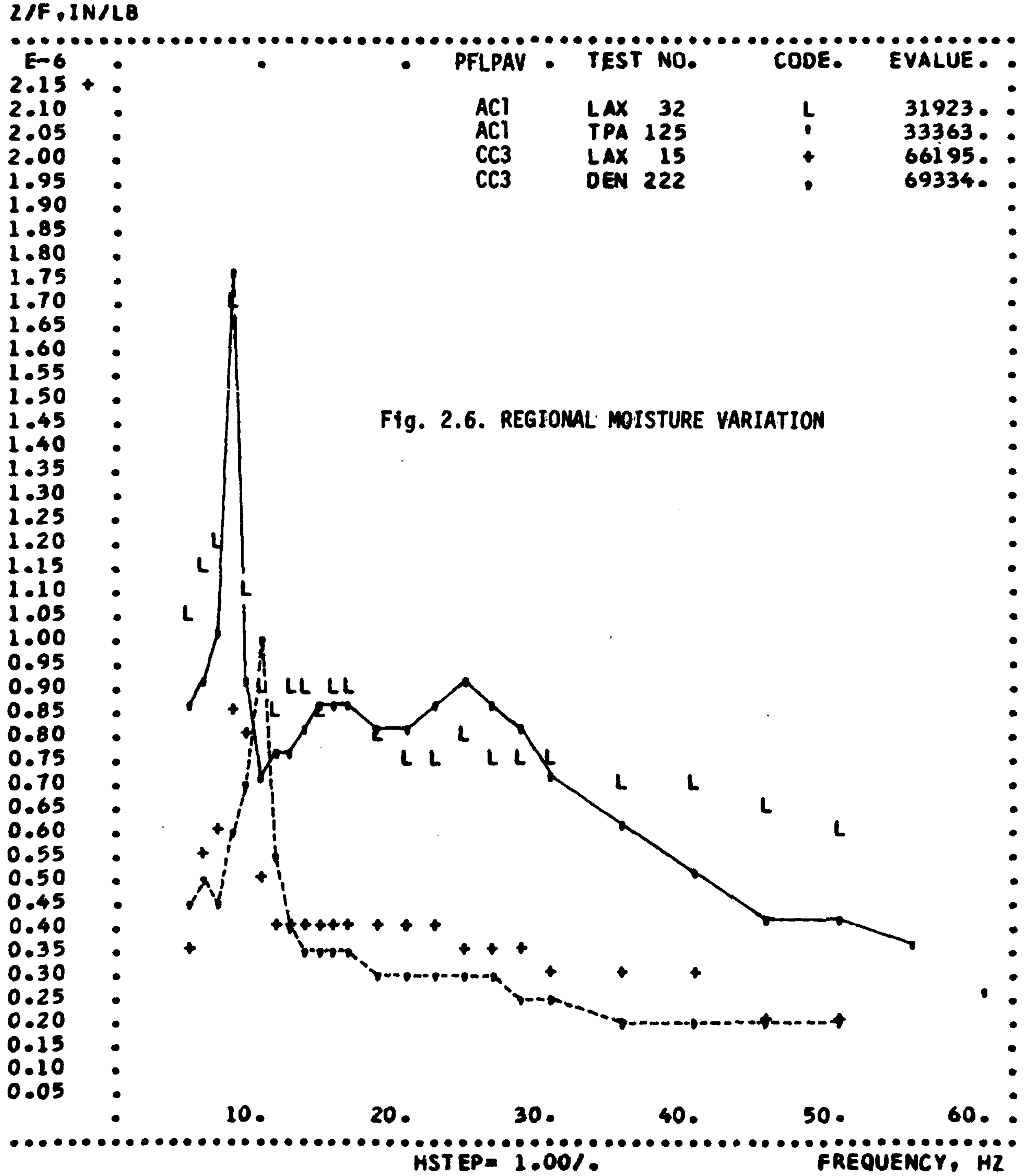

Fig. 2.6. REGIONAL MOISTURE VARIATION

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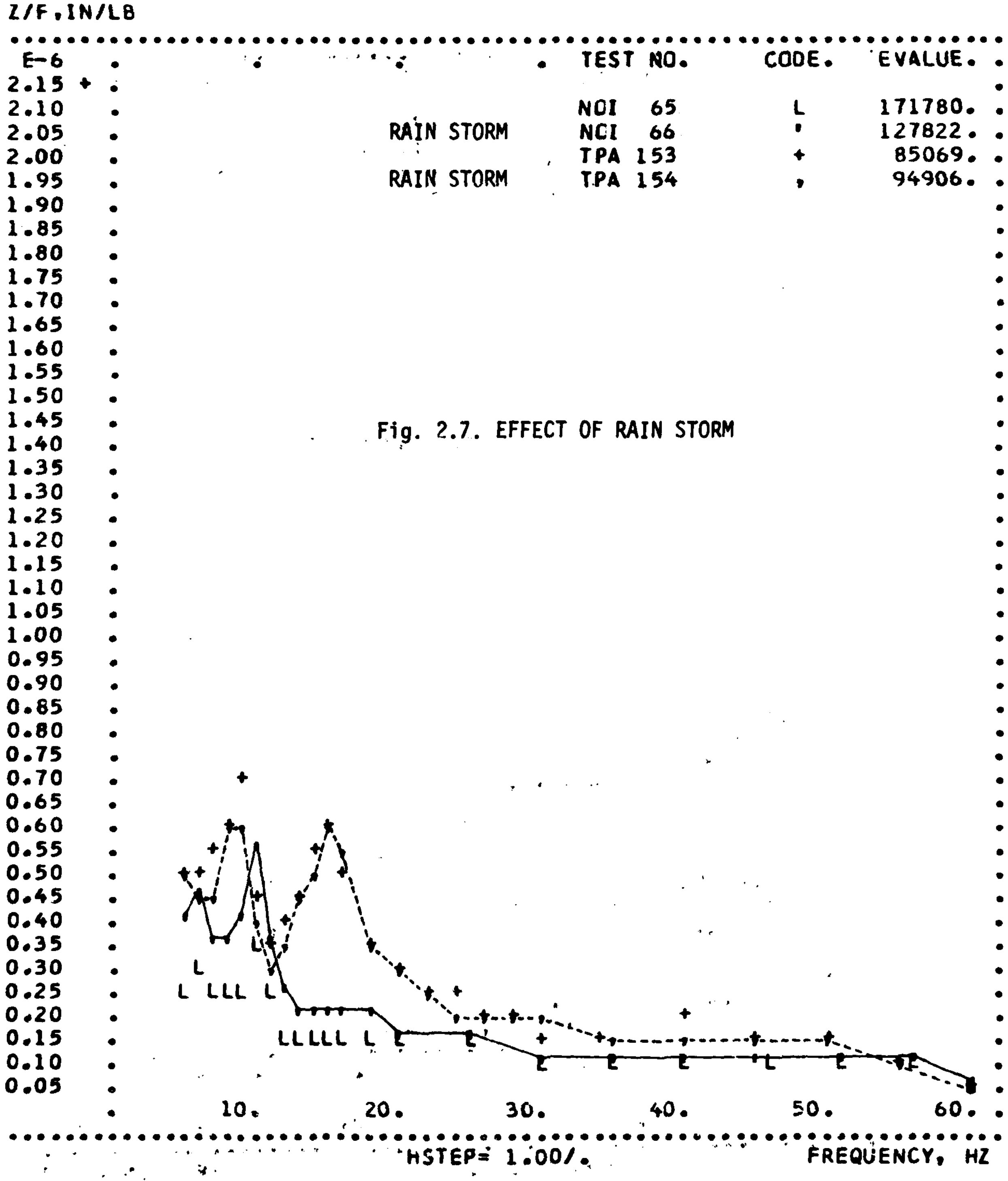

Fig. 2.7. EFFECT OF RAIN STORM

NDT PLOT

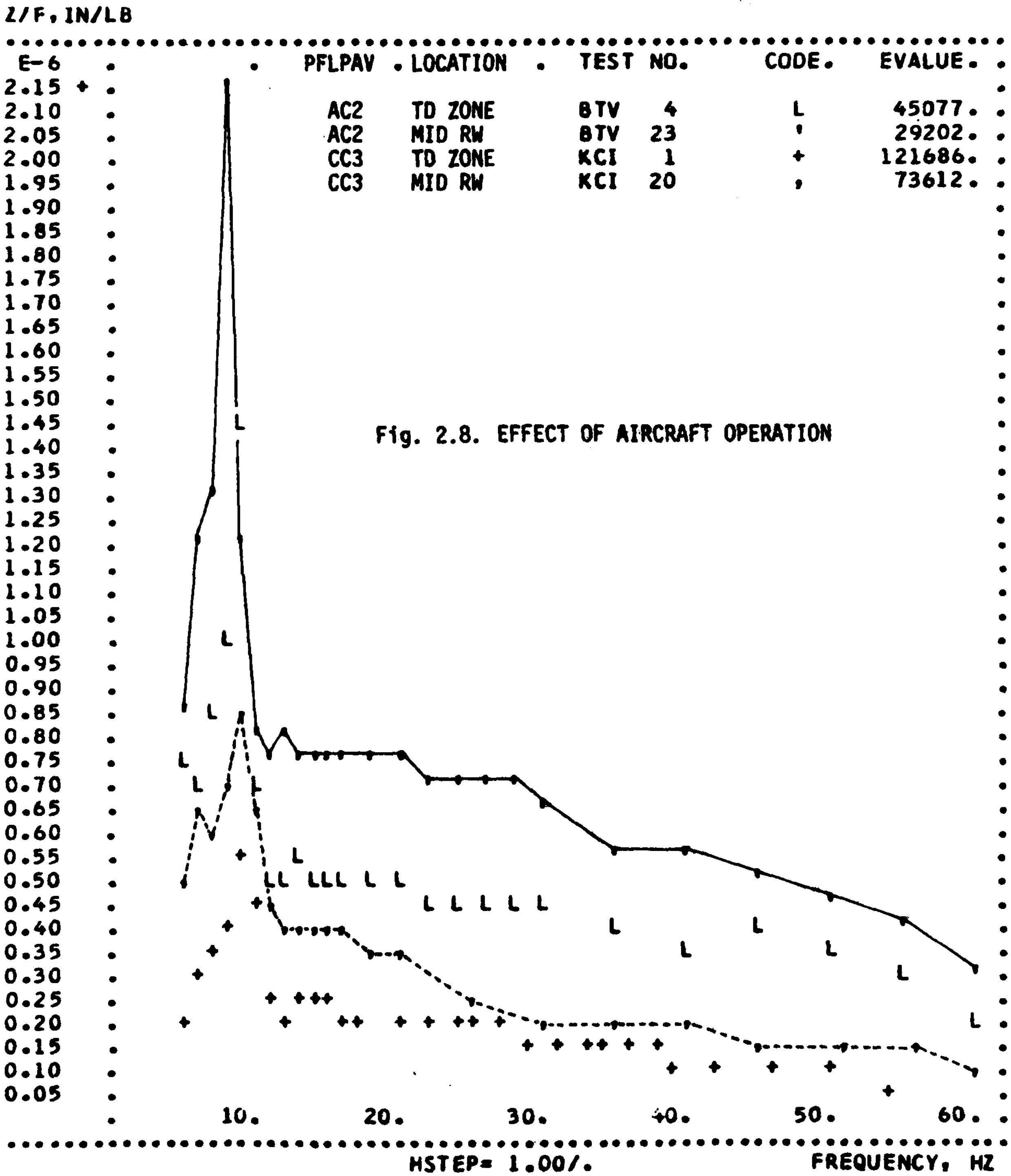

Fig. 2.8. EFFECT OF AIRCRAFT OPERATION

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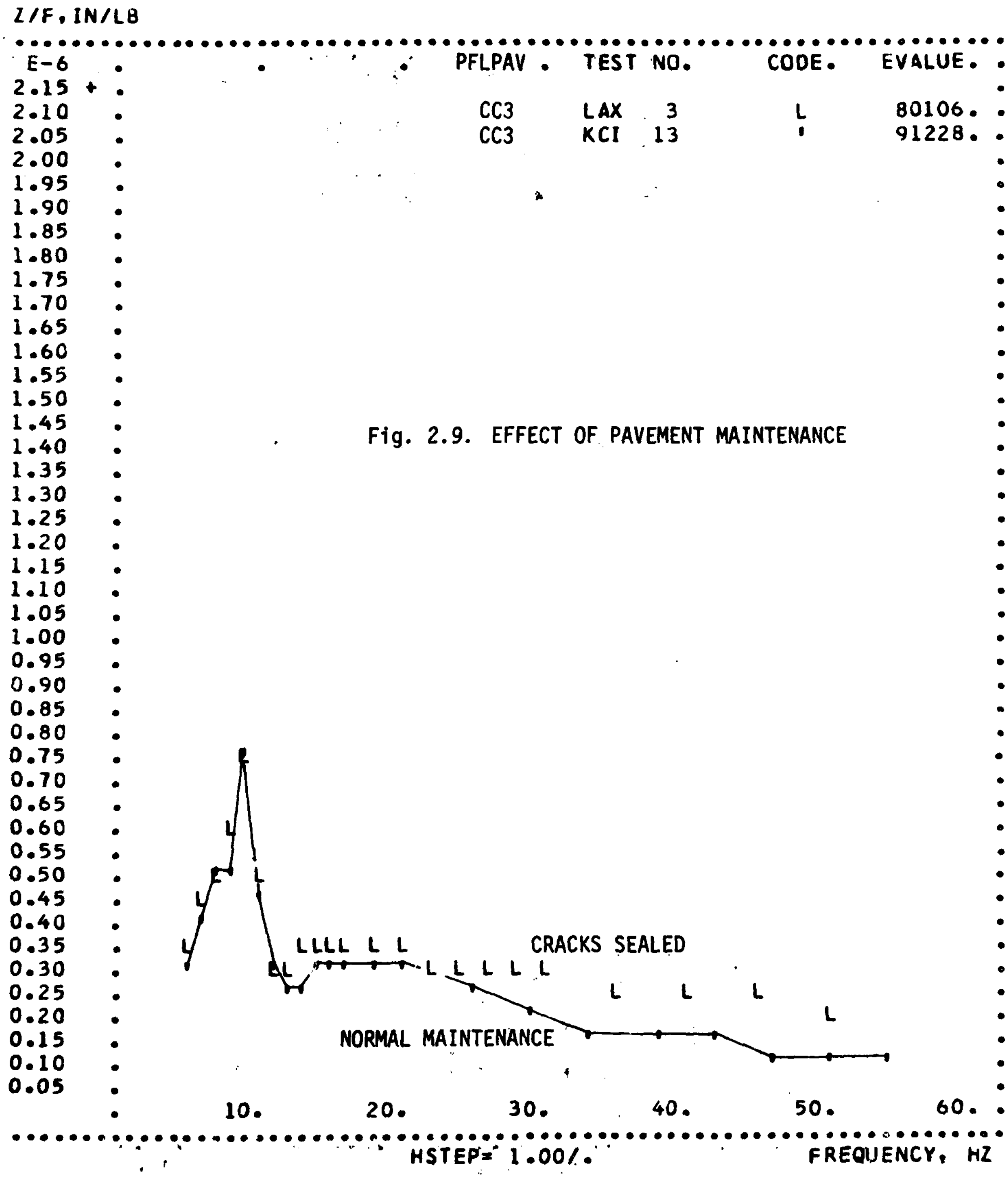

Fig. 2.9. EFFECT OF PAVEMENT MAINTENANCE

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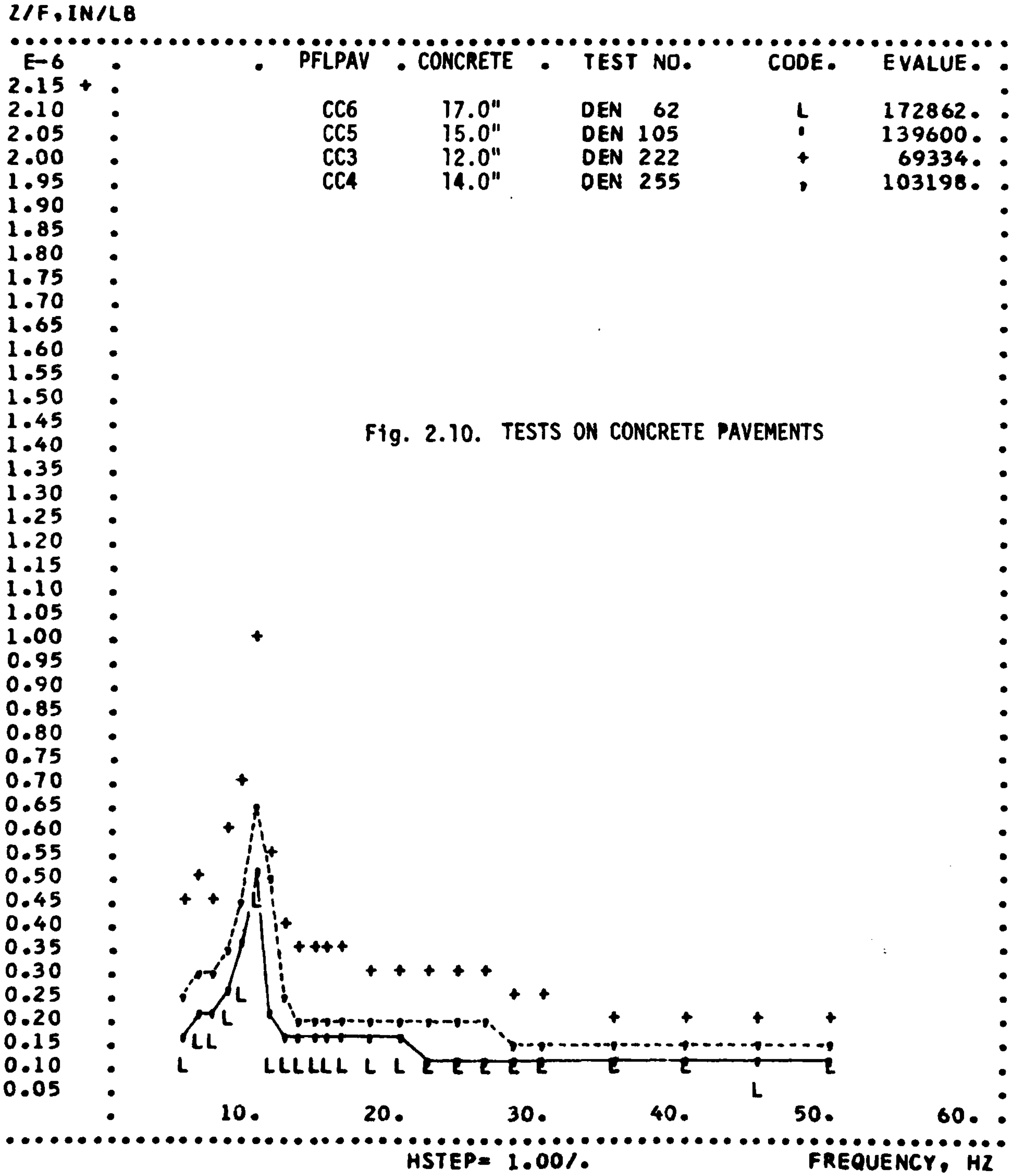

Fig. 2.10. TESTS ON CONCRETE PAVEMENTS

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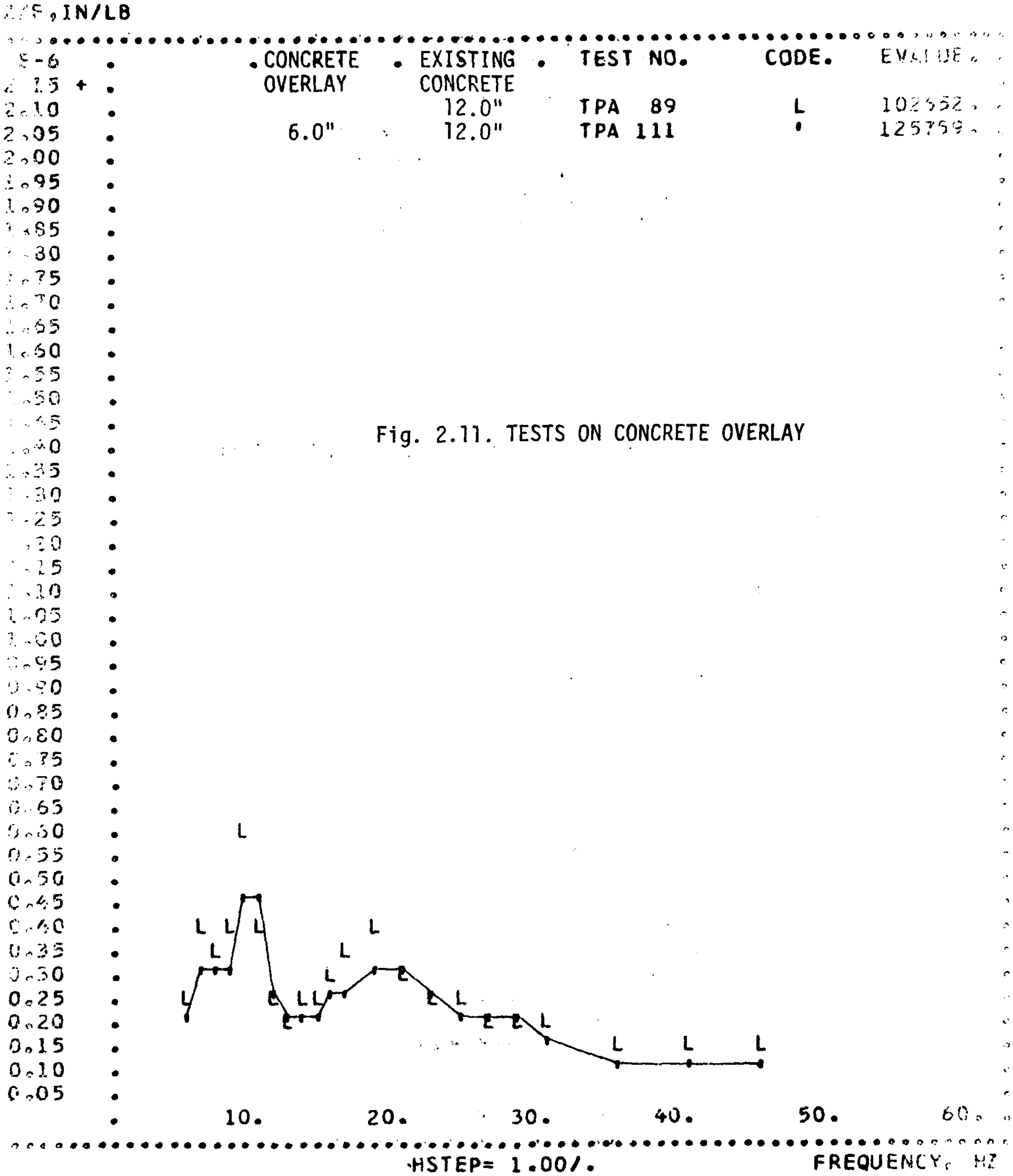

Fig. 2.11. TESTS ON CONCRETE OVERLAY

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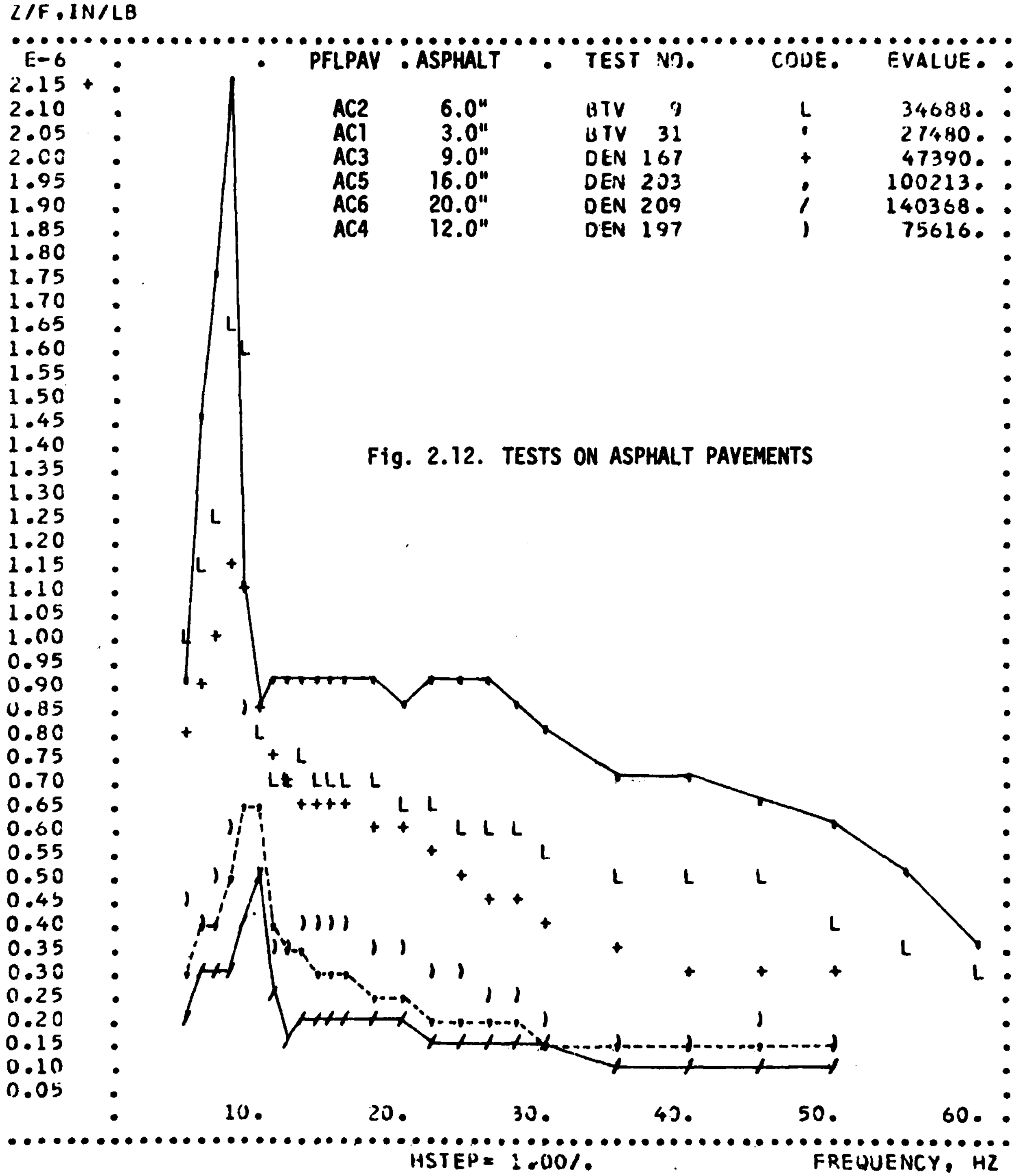

Fig. 2.12. TESTS ON ASPHALT PAVEMENTS

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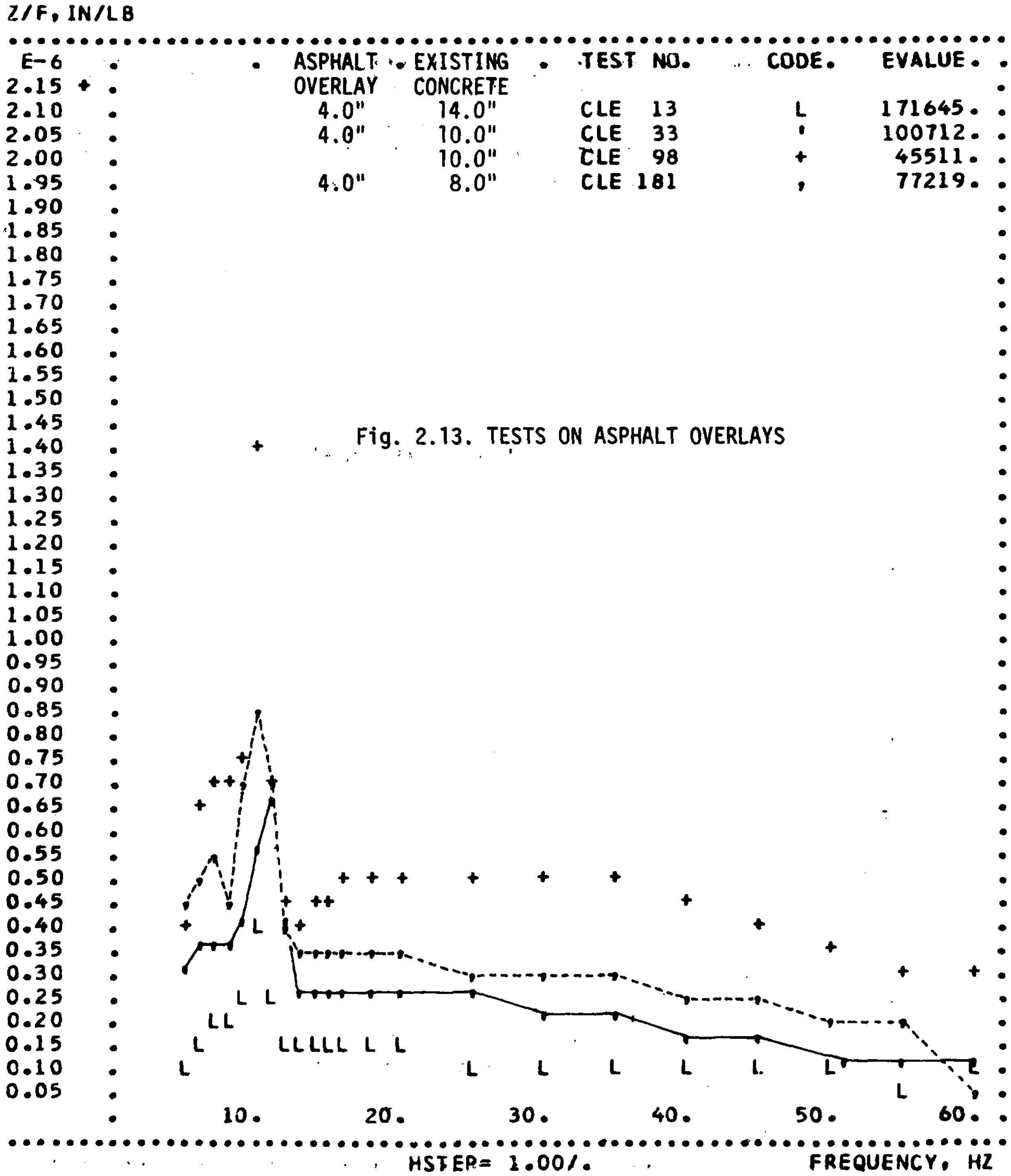

Fig. 2.13. TESTS ON ASPHALT OVERLAYS

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NDT PLOT

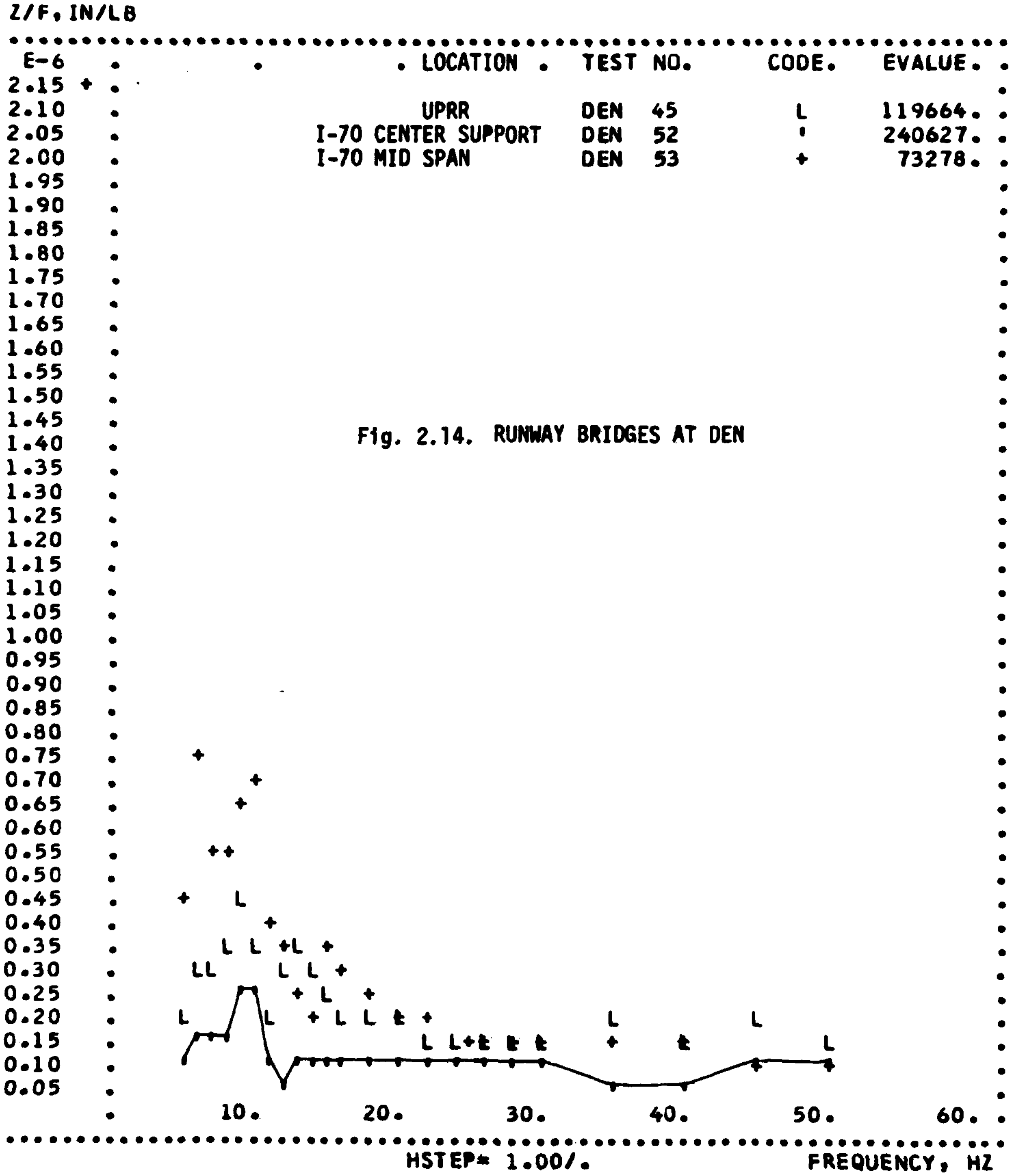

Fig. 2.14. RUNWAY BRIDGES AT DEN

NDT PLOT

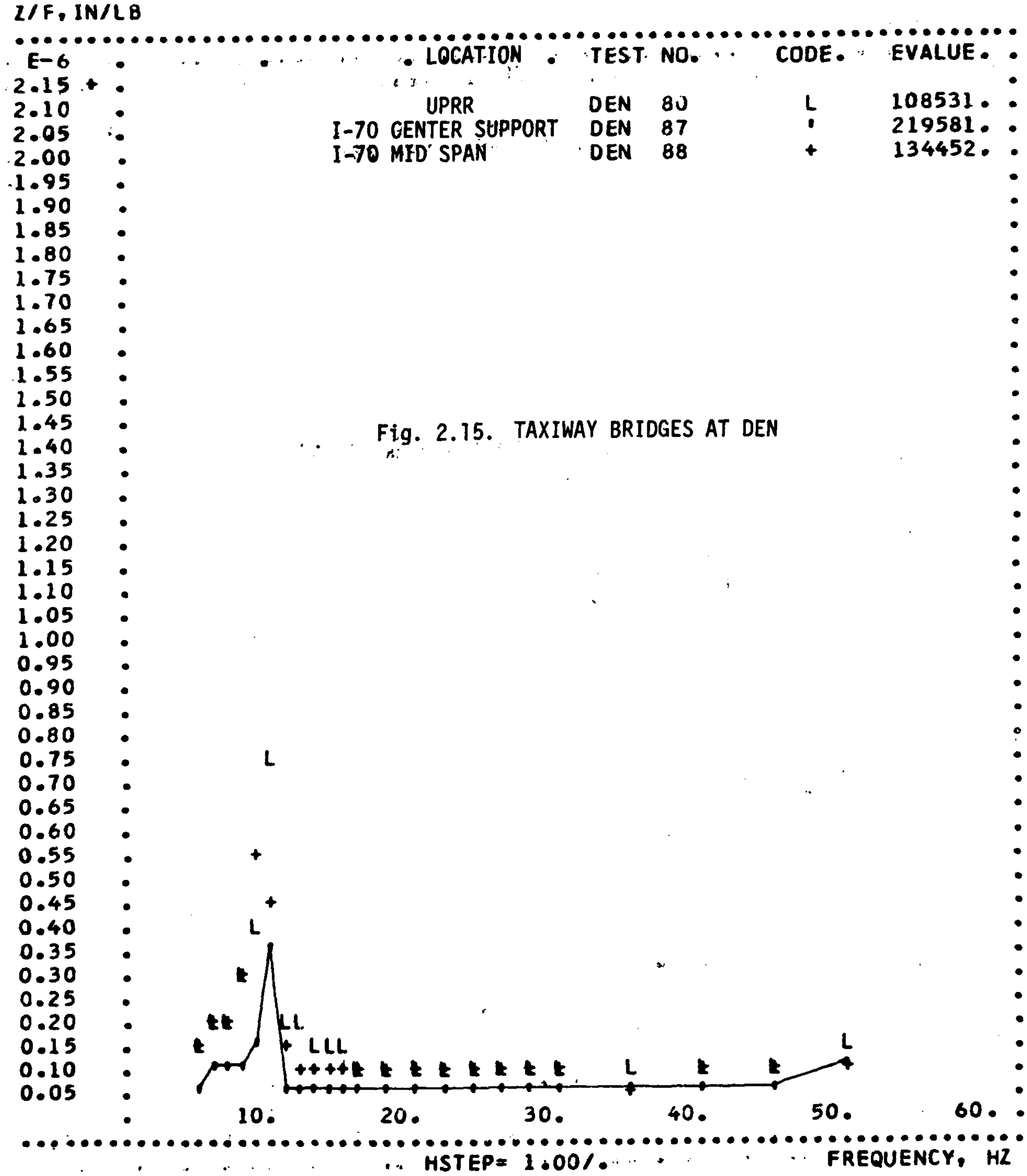

Fig. 2.15. TAXIWAY BRIDGES AT DEN

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NDT PLOT

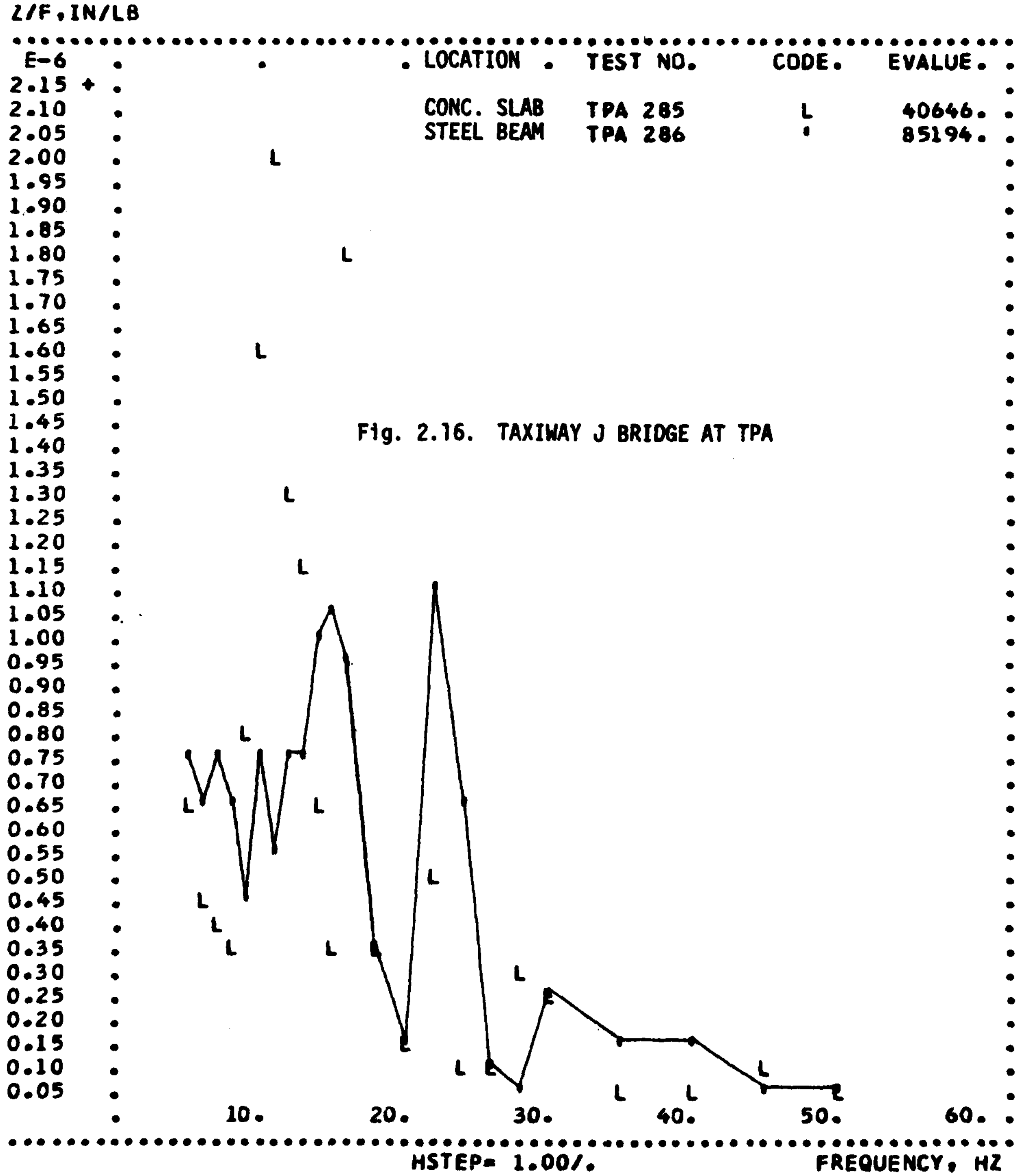

Fig. 2.16. TAXIWAY J BRIDGE AT TPA

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NDT PLOT

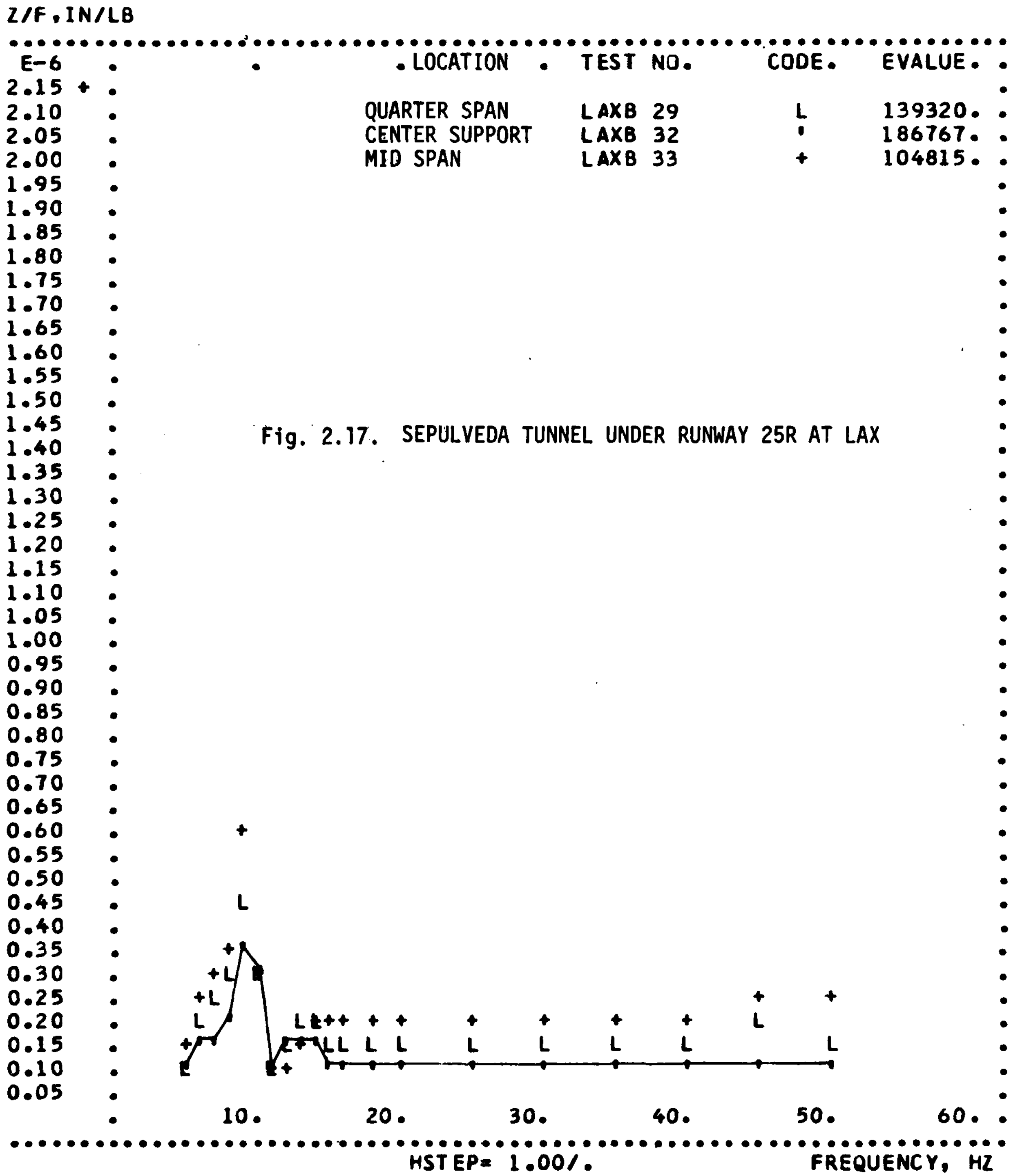

Fig. 2.17. SEPULVEDA TUNNEL UNDER RUNWAY 25R AT LAX

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NDT PLOT

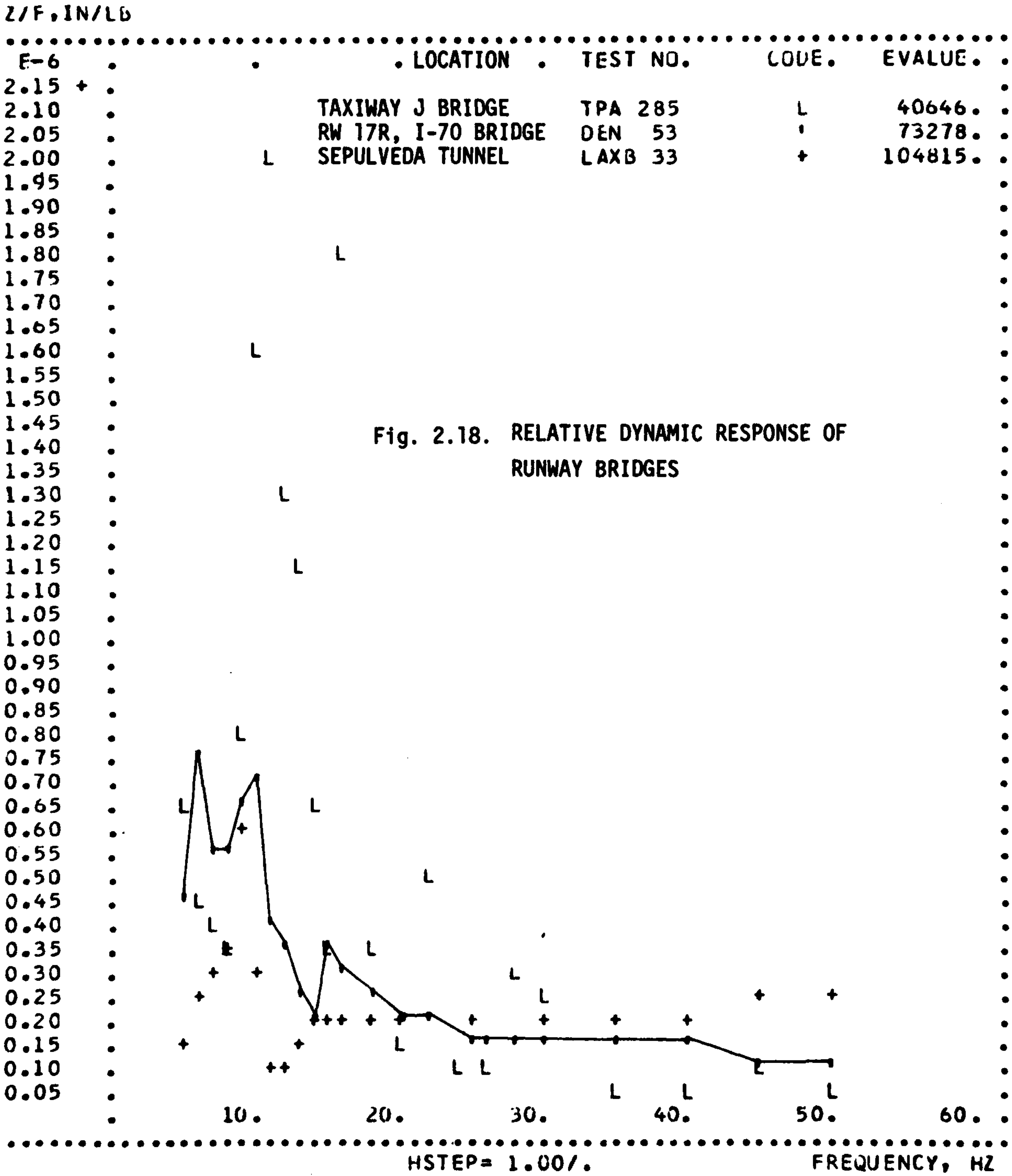

Fig. 2.18. RELATIVE DYNAMIC RESPONSE OF RUNWAY BRIDGES

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NDT PLOT

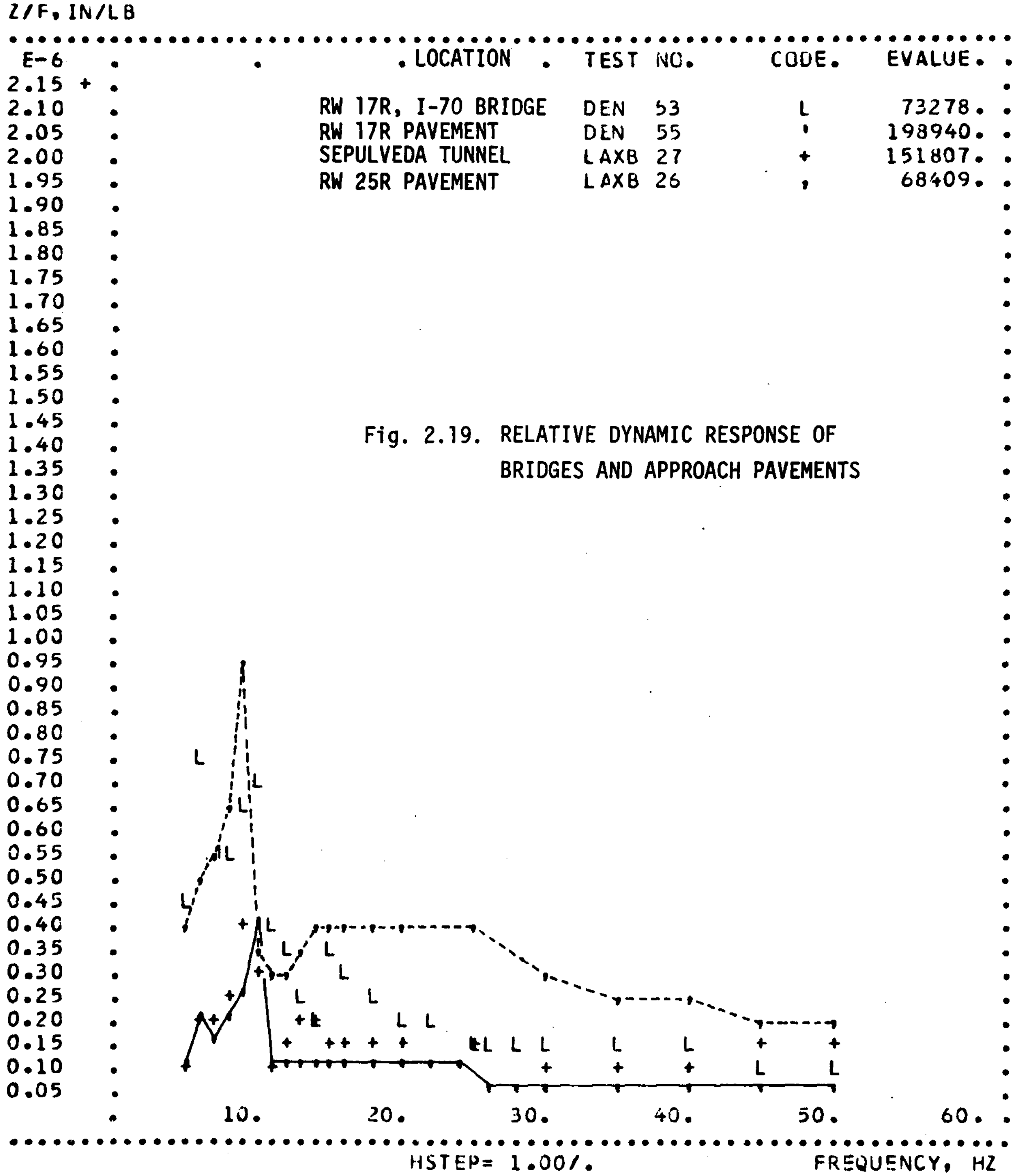


Fig. 2.19. RELATIVE DYNAMIC RESPONSE OF BRIDGES AND APPROACH PAVEMENTS

PART THREE CORRELATION BETWEEN CURRENT FAA STANDARDS AND FUNCTIONAL PAVEMENT DESIGN METHOD

In current FAA standards, the methods of pavement design can be divided into two groups: (1) empirical and semi-empirical approach for asphalt concrete pavement and (2) theoretical analysis for portland cement concrete layer. The FAA design procedure is further classified by four sets of soil identifications and drainage conditions. With the increasing operation of giant air transports in recent years, an effective nondestructive evaluation and design method for airport pavement is needed. The cost benefit balanced pavement design method will reflect the airport operation parameters such as aircraft speed, dynamic response, pavement roughness, air-ground navigation, user's demand forecast, maintenance needs, fiscal obligation and interference due to pavement construction. The NDT frequency sweep concept and functional pavement design method were originally developed to meet such demands for the pavement construction at JFK, LGA and Newark Airports. Subsequently, the design method was refined and modified during its application to other hub airports. The sequence of engineering development of this design method is briefly outlined in the following paragraphs:

DEFINING PURPOSE OF PAVEMENT The purpose of modern airport pavement is to provide a functional and smooth surface for safe operation of aircraft at reasonable cost-benefit consideration.

MECHANISTIC MODEL A mechanistic design theory can be applied even without the benefit of past rxperience by determining the physical requirements of the pavement structure based on the anticipated condition of external loads, postulated deformations, stress in the elements and the mechanical behavior of materials under various loading conditions according to the basic laws of mechanics governing the motion and force. The relationship between elements is complicated by the physical and geometric parameters of the pavement system. For that reason, the theory must be simplified to fit into the assumed boundary conditions. Therefore, the validity of the mechanistic model shall depend on the accuracy of assumptions. The mechanistic model used in the early functional pavement analysis, prior to 1970, was the equilibrium equations by Boussinesq. The current model used in the computer program is the general equilibrium of layered system, originally developed by Burmister, programmed by Chevron and substantially modified for multi-wheel and iterative operation. A finite element program is in process to supplement the stress analysis at pavement joints and other discontinuities.

EXPERIMENT The application of mechanistic analysis requires the experimental development of input parameters either in the laboratory or in the field. For a pavement system, limited tests in the laboratory or in the field generally do not develop sufficient information for the total system. The input parameters used in the current functional pavement design program were basically derived from the field test program at Newark Airport, pp. 363-382, Ref. [1], which, as of 1979, is still the largest and most comprehensive test track for airport pavements. In order to alert the program user to the complex and complicated nature

of pavement system, all input parameters developed from Newark and JFK experiments, including refinements at other airport tests, will be termed as "Default Values" in the computer program. The values are actually not in default but its impact should be studied by the program user.

PROBABILISTIC MODEL All natural events, such as construction, materials, aircraft operations and human judgment are subject to random variation. There is no single set of values which can be used to represent a common event. The probabilistic model used in engineering analysis indicates that it is possible to predict the trend of what is likely to happen on the basis of statistical analysis of the past, provided that all contributing factors remain unchanged. For the current functional pavement design program, probabilistic models and reliability analysis have been used extensively in developing pavement design parameters, such as traffic distribution, surface roughness, aircraft vibration, material characteristics, stress-strain behavior of pavement layers, landing impact, moisture migration, quality control, soil distribution and many other factors.

OBSERVATION AND FEEDBACK For improving the ultimate reliability of the current functional pavement design program, it is necessary to continue field observation and experiments during the design, construction and operation of pavement system at airports. This constant research and feedback will convert past unknown into valuable experience. With progressive modifications and refinements in the past ten years, the current functional pavement design program is much more reliable, definitive, and precise in defining the parameters of pavement design than when it was originally developed for JFK-Newark Airports in 1967.

With this background information on the development of functional pavement design methods, it is not appropriate for the author to compare the FAA design standards with the frequency sweep functional pavement design method. In order to comply with the contract requirements, factual analysis were made to understand the FAA design standards. The results are shown in Table 3.1. and the following articles.

3.1. DSM AND E-VALUE BY FREQUENCY SWEEP METHOD

The DSM value as defined in the current FAA standards is the tangent modulus of dynamic load-deflection function at 15 Hz by NDT load sweep method. It can be expressed by:

$$DSM = F/z \text{ in kips per inch}$$

in which F = Forcing amplitude, peak to peak, in kips
z = Dynamic response at steady state of vibration, in inch.

For the NDT frequency sweep method, the E-value is equal to

$$E = 1/(2a*SUMZ)$$

in which a = radius of test plate, in inches
SUMZ = quasi-static deflection, in inch per lb.

There should be a statistical correlation between the E-value and DSM. During the NDT evaluation for five FAA validation airports and, also for Cleveland and New Orleans, statistical correlations were recorded

Table 3.1 COMPARISON OF FAA DESIGN STANDARDS AND FREQUENCY SWEEP FUNCTIONAL PAVEMENT DESIGN

	FAA Standards A/C 150-5320 -11	FAA Standards A/C 150-5320 -6B	Functional Design/NDT	Reference
Pavement Support				
Identification	No	Yes	No	
Characterization	Yes	Yes	Yes	Art. 3.1.
Effect of Moisture	No	Yes	Yes	
User's Requirements				
Classification		Yes	No	
Demand Forecast		No	Yes	
Traffic Distribution		Yes	Yes	
Functional Requirements				
Aircraft Operation		Yes	Yes	
Maintenance Needs		No	Yes	
Present Functional Life		No	Yes	
Pavement Design				
Universal Design Method		No	Yes	
Mechanistic Concept				
System Equilibrium		No	Yes	
Fatigue Stress		Yes	Yes	
Deflection Criterion		No	Yes	
Material Characterization				
Static and Dynamic Strength		No	Yes	
Time and Temperature Effects		No	Yes	
Quality Variation		Yes	Yes	
Volumetric Change		Yes	Yes	
Design Charts				
Asphalt Pavement		Yes	Yes	Art. 3.2.
Concrete Pavement		Yes	Yes	Art. 3.3.
Stabilized Pavement		?	Yes	
Overlays		Yes	Yes	Art. 3.4.
Optimization and Cost Benefit Analysis		No	Yes	

between E-values and DSM (see Table 3.2). The best correction, based on the result of more than 1600 tests, is:

EPAV = 29*DSM for 18" dia. test plate.

This equation has been introduced in the default values file. Thus, the computer program for functional pavement design method can be used for pavements having DSM inputs only.

3.2. DESIGN OF ASPHALT PAVEMENT

The FAA standards for designing asphalt pavement is basically the CBR method developed by the Corps of Engineers in the 1950's for the aircraft loads of 200,000 lbs. and progressively modified for today's aircraft loading. In the pavement engineering profession, the use of the CBR method and its modifications exceeds the use of all other methods combined. At the inception of the CBR method, modern soil mechanics in gradation, Atterbery limits and sample tests were adopted together with the CBR test in characterizing the pavement support. Subsequently, the CBR curves were modified based on job experience and field load tests.

In recent years, attempts have been made by the Corps of Engineers to introduce the CBR experience in elastic layer analysis. The E-value of subgrade support is assumed to be 1500(CBR) which is based on the correlation developed by Foster-Heukelom in 1960, Ref. [3]. The NDT machine used by them is very similar to that used at Newark. The author's experience indicates that the stiffness modulus measured by the Shell machine is higher than that measured by the current WES machine. Possibly, the CBR conversion factor will be smaller than 1560 found by Foster-Heukelom. For the purpose of discussion, if the diameter of CBR load piston is used in the Boussinesq equation, the theoretical conversion factor is 120. The reliability of using CBR experience in elastic layer analysis depends on the selection of conversion factor which may range from 120 in theoretical analysis to 1560 resulting from the Shell tests.

The mechanistic model used for the functional pavement design is simply the general equilibrium of layered system. Design charts for limiting surface deflection and layer stress have been constructed for many types of pavement compositon. A set of design charts for a typical asphalt pavement is shown in Figs. 3.1 and 3.2. A CBR curve is plotted in Fig. 3.3 which is based on information given in A/C 150-5320-6B. For the curve shown in Fig. 3.3, a CBR-E conversion factor of 500 was used. During the NDT validation, core borings were taken to determine the thickness of asphalt layer, and lab tests were performed by Majidzadeh to estimate the E-value of subgrade. The results are plotted in Fig. 4.8. The CBR assignment for the soil classification as given in the FAA standards is on the low side of laboratory test and, therefore, the CBR assignment compensates the effect of high conversion factor of 1500. A realistic conversion factor is likely to range from 300 to 600(CBR).

In studying Fig. 3.3, it seems that in the lower range of ESUB value, the thickness requirement of asphalt layer for limiting surface deflection is greater than that provided by the CBR design. Deflection and ruttin^

Table 3.2 STATISTICAL CORRELATION BETWEEN NDT E-VALUE AND WES-DSM

Tests on Existing Pavements - 18-inch Diameter Plate

AIRPORT	NO.TEST	ΣDSM E06	ΣE E08	ΣDSM*E E11	ΣDSM**2 E10	ΣE**2 E13	A	B	R	DSM/E
Cleveland	187	.709	.196	.858	.311	.240	26.67	3322.	.93	45.0
New Orleans	167	.605	.148	.635	.265	.153	21.67	9952.	.97	40.2
Kansas City	226	.729	.199	.678	.252	.186	21.73	17222.	.80	38.2
Burlington	112	.167	.049	.101	.030	.304	29.93	-393.	.99	34.0
Tampa	262	.740	.249	.871	.278	.290	23.98	27443.	.87	28.8
Denver	278	1.490	.380	2.460	1.020	.615	19.51	32170.	.94	37.2
Los Angeles	377	.729	.258	.625	.201	.207	21.79	27222.	.94	25.8
7 Airports	1609	5.169	1.479	6.228	2.363	1.721	20.95	24600.	.92	34.3

Default values used in computer program E = 29.*DSM

Tests on Subgrade - 30-inch Diameter Plate

AIRPORT	NO.TEST	ΣDSM E04	ΣE E06	ΣDSM*E E08	ΣDSM**2 E07	ΣE**2 E10	A	B	R	DSM/E
Burlington	13	.838	.151	.979	.544	.177	16.24	1134.	.77	55.8
Tampa	5	.248	.056	.298	.129	.070	27.92	-2468.	.96	44.4
2 Airports	18	1.086	.208	1.277	.673	.247	12.22	4184.	.66	52.6

Linear Correlation: E-value = A*DSM + B
Correlation Coefficient = R

A = (ΣDSM*E - (ΣDSM)*(ΣE)/N)/(ΣDSM**2 - (ΣDSM)**2/N)
B = (ΣE)/N - A*(ΣDSM)/N
R = A*SQRT((ΣDSM**2 -(ΣDSM)**2/N)/(ΣE**2 - (ΣE)**2/N))

are experienced from channelized traffic. In the higher range of ESUB value, CBR design provides thinner pavement than that required for limiting layer stress. Overstress of asphalt layer and the appearance of hook shape cracks parallel to the wheel path will be anticipated. CBR design is empirical and generally provides thickness that are in between the thickness required by the limiting layer stress and surface deflection, if the CBR conversion factor is correct.

3.3. DESIGN OF CONCRETE PAVEMENT

The FAA standards for designing concrete pavement was based on development of the Corps of Engineers in the 1940's at its Ohio River Division Laboratories. Instrumented test pavements were subjected to accelerated traffic. The results of the pavement behavior led to a modification of Westergaard theoretical analysis. During the same period, Pickett and Ray introduced influence charts which have been used extensively in concrete pavement design. A mechanistic pavement design method was, therefore, introduced.

In recent studies, Ref. [4] and [5], Crawford et al have concluded that "the peak (concrete) pavement stress can ususally be computed by either (Westergaard or elastic layer) method of analysis while the peak displacements are separated by a rather consistent seventy percent (smaller deflection by elastic layer method)." Because the criteria of FAA standards concern only the peak tensile stress of concrete layer, the GELS design, such as those shown in Fig. 3.5 are valid. Fig. 3.6 shows good comparisons of design curves between GELS and FAA standards if the conversion factors are correct. Moreover, design experience of high speed runway pavement indicates that the limiting deflection criteria do not normally control the design condition. The FAA design standards and the functional pavement design program are compatible for concrete pavement. The fatigue strength of concrete material has been incorporated in the functional pavement design. This procedure can be easily adopted in the FAA standards for evaluating the allowable stress of concrete.

3.4. DESIGN OF OVERLAYS

There was no overlay design procedure in the early version of FAA standards. In recent years, some design approaches have been attempted.

ASPHALT OVERLAY The basic concept is borrowed from the equivalent-layer method sponsored by the AASHTO and Asphalt Institute for highway pavements. A group of equivalency numbers was developed for various pavement layers under different service conditions. The major control value is that the summation of equivalent layers shall meet the requirements of basic CBR design. Thus, the validity of asphalt overlay design depends on the assumption of the equivalency coefficients.

CONCRETE OVERLAY The summation of the square of thickness was originally developed by the Ohio River Division Laboratories of the Corps of Engineers in the 1940's. The concrete overlay is assumed to have no shear connection with the existing pavement. Subsequently, a set of coefficients was introduced to indicate the structural integrity of existing pavement and the effect of bonding strength. Similar to equivalency coefficients for asphalt overlay, the reliability of structure coefficients dominates the validity of FAA concrete overlay design.

3.5. DISCUSSION ON GELS COMPUTER PROGRAM

The GELS program is based on the equations of equilibrium which are expressed in terms of stress function. A unique solution can be obtained if and only if the stress function satisfies the equilibrium equations and compatibility equations. The computation is reduced to the solution of stress function, which is a partial differential equation subject to the boundary condition at the surface, at the interfaces and at infinite depth. The external load used in the GELS program is assumed to be axially symmetrical cylindrical coordinate system and normal to the surface. It is expressed by $p(m)Jo(mr)$ where $p(m)$ is an arbitrary function of the parameter m and $Jo(mr)$ denotes the Bessel function of the first kind of order zero. A stress function of the form:

$$\phi = Jo(mr)(A+Bz)e^{mz} + (C+Dz)e^{-mz}$$

has been used for the computer operation.

Extensive computer experience of GELS operation suggests that:

1. The error due to truncation of Bessel function is noticeable in stress computation of thin layer of asphalt concrete, say less than 4" in thickness of asphalt pavement.
2. The computed surface deflection of high strength pavement layer, such as portland cement concrete, seems to be much lower than the measured deflection by NDT. Similar findings were reported by Crawford et al, Ref. [4].

In the final design, special attention will be given to the design of thin asphalt layers. For concrete pavement design, the surface deflection is normally not the limiting factor. GELS computer program is applicable for stress criterion.

3.6 SURVEY OF JOB APPLICATIONS

The design of airport pavements using the FAA design standards depends primarily on: (1) soil classification, (2) the assignment of CBR and k-value, (3) layer equivalency coefficients for asphalt overlays and (4) structural coefficients for concrete overlays. Pavement thickness varies according to the values of the parameters used in accordance with FAA Advisory Circular 150-5320-6B. The stated FAA position is that the Advisory Circular provided guidance to the public for the design and evaluation of pavements at civil airports, and that engineering professionals must exercise their professional judgment in creating a final pavement design. Consequently, close comparison of the results by FAA standards and pavement

designs by GELS may not be obtained. As of November, 1978, NDT functional pavement design has been used at fifteen hub airports including the four selected for the FAA validation program. The actual job application of the NDT functional design concept can be grouped as follows:

FULL APPLICATION AIRPORTS   The pavement design was based on the NDT functional performance concept. All pavement constructions were completed and the finished facilities have been placed in daily service. ADAP participation were approved by the FAA regional office with the concurrence of Airport Service in Washington, D.C. for the evaluation by the frequency sweep NDT and functional design concepts. The listing of these airports are:

AIRPORT	FACILITIES	YEAR OF CONSTRUCTION
JFK	TWs O and I	1968-1970
Newark	Entire Airfield	1968-1978
Portland, Oregon	RW 10R Extension	1972-1974
New Orleans	Two RWs and TWs	1976-1978

EVALUATION STAGE AIRPORTS   There are seven airports where all pavements have been tested and evaluated by NDT functional concept. Final decision on the pavement design program is still in process. These airports are:

AIRPORT	YEAR OF TEST AND EVALUATION
Los Angeles, Ca.	1978
Burlington, Vt.	1977
Tampa, Fl.	1978
Kansas City, Mo.	1976
Ontario, Ca.	1977
San Jose, Ca.	1975
San Diego, Ca.	1978

INDEPENDENT FINAL DESIGN   After NDT functional evaluation was concluded, management at four hub airports retained their engineering staff or outside consultants to complete the final pavement design. Construction of the pavements at the four airports have been completed. The design, construction and ADAP participation were approved by the FAA. A comparison of the final designs by the FAA standards and functional design is shown in Table 3.3. It is noted that:

1. For Cleveland Hopkins International Airport, the design changes from the estimate, the subsequent modification, and the final design as shown on FAA Form 5100-1 indicate the dilemma encountered in interpreting A/C 150-5320-6B.
2. Pavement program at Raleigh Durham was designed by the airport engineering staff. Airport operation and cost effectiveness were considered in the final design.
3. At Nashville, the overlay of RW13-31 was designed by the airport engineering staff with reference to the earlier NDT functional design. The airport authority spent several hundred thousand dollars less in construction cost than the amount authorized by the FAA. For RW2L-20R, the final pavement overlay was designed by an independent consultant.
4. Similarly, the overlay for RW8R-26L at Denver was also designed by an independent consultant.

CONCLUSION In reviewing these job applications, the FAA standards A/C 150-5320-6B is subject to divergent interpretations and requires no cost effectiveness study for pavement design. Pavement evaluation using functional design concepts can provide pavement thicknesses comparable to those required by FAA standards if the interpretation of FAA design parameters are correct. Moreover, the functional design method provides a cost benefit study indicate evaluate the economic aspects of a pavement system.

Table 3.3 THICKNESS DESIGN BY FUNCTIONAL PAVEMENT CONCEPT AND FAA STANDARDS INTERPRETED BY AIRPORT ENGINEERS?CONSULTANTS

AIRPORT FACILITY	STATION	FUNCTIONAL DESIGN/NDT	INTERPRETATION OF A/C 150-5320-6B ESTIMATE	MODIFIED	FORM5100-1
CLEVELAND		AC-OVERLAY	AC-OVERLAY	AC-OVERLAY	AC-OVERLAY
RW 5R-23L	0.-27.	NO NEED	10.0" P401	8.0" P401	0.0" P401*
	27.-63.	5.1" AC	14.0" P401	8.0" P401	5.5" P401*
	63.-85.	4.0" AC	18.0" P401	5.5" P401	4.0" P401*
	85.-90.	4.0" AC	19.0" P401	4.0" P401	4.0" P401*
RALEIGH-DURHAM		AC-OVERLAY			AC-OVERLAY
RW 5-23	0.-25.	6.0" AC			2" P401+4" P201
	25.-64.	8.0" AC			2" P401+6" P201
	64.-75.	NO NEED			2" AC Levelling
NASHVILLE		AC-OVERLAY			
RW 13-31	0.-78.	8.5+10" AC			8.5"AC-OVERLAY
RW 2L-20R	0.-75.	8.0+10" AC			14.0"CONC.-OVER*
DENVER		AC-OVERLAY			CONC-OVERLAY
RW 8R-26L	1.-31.	8.3+10.0"AC			15" P501+3" P201*
	31.-69.	9.3+10.7"AC			15" P501+3" P201*
	69.-99.	5.3+10.2"AC			15" P501+3" P201*

NOTE: * Denotes final pavement design performed by consultants.

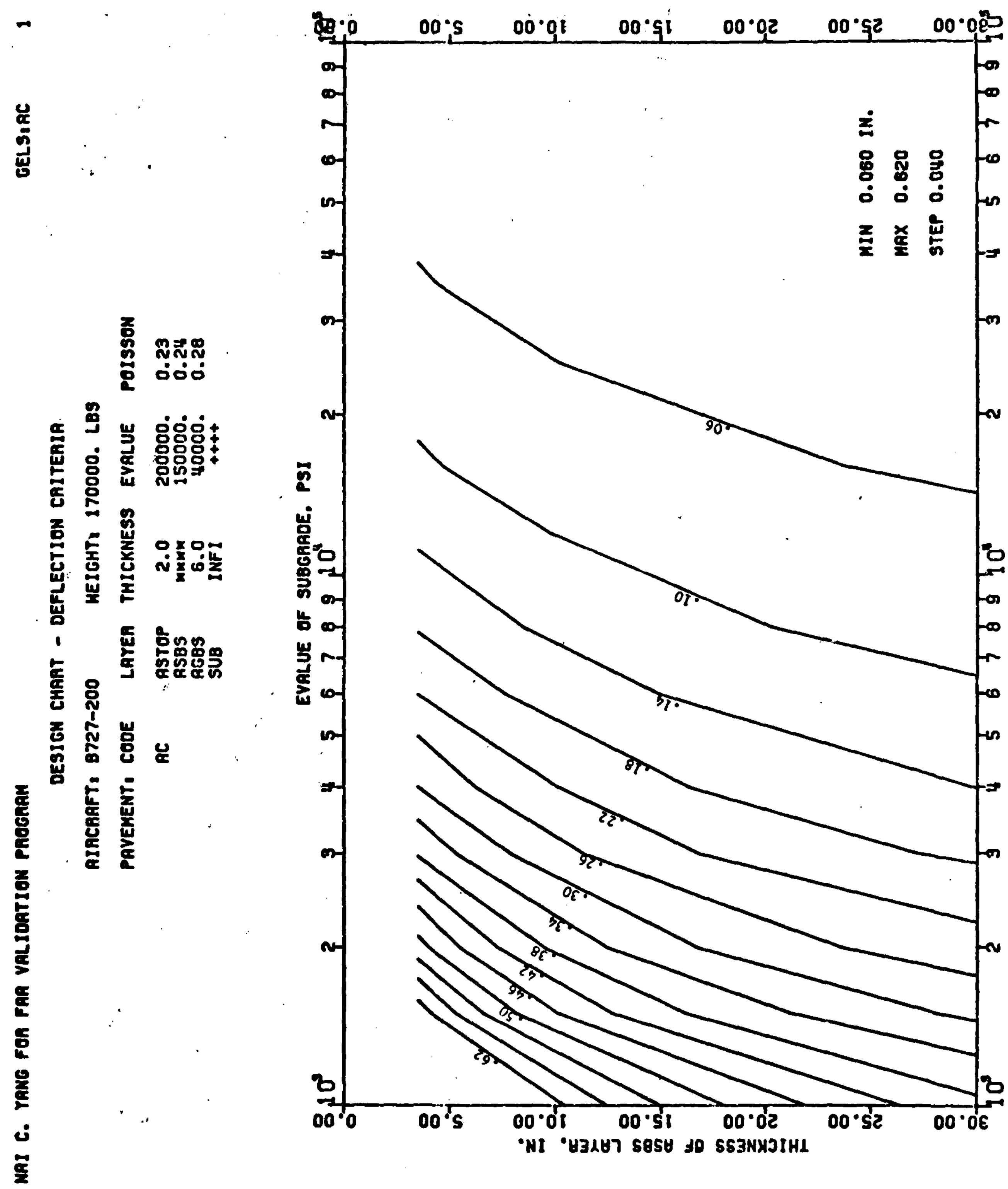


Fig. 3.1. Asphalt Pavement Design Curves for B727 Operation Limiting Deflection Criteria.

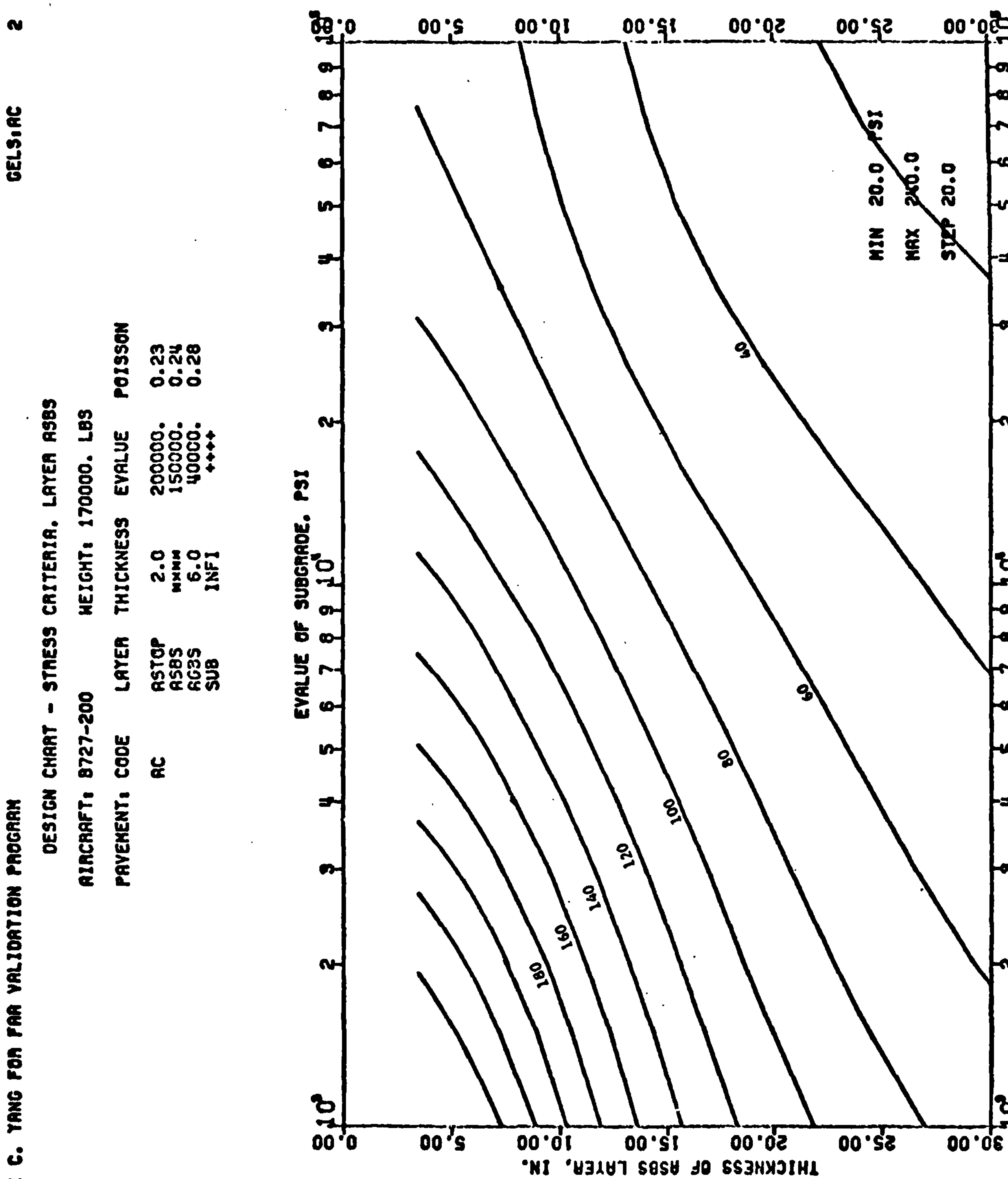


Fig. 3.2. Asphalt Pavement Design Curves for B727 Operation Limiting Stress Criteria.

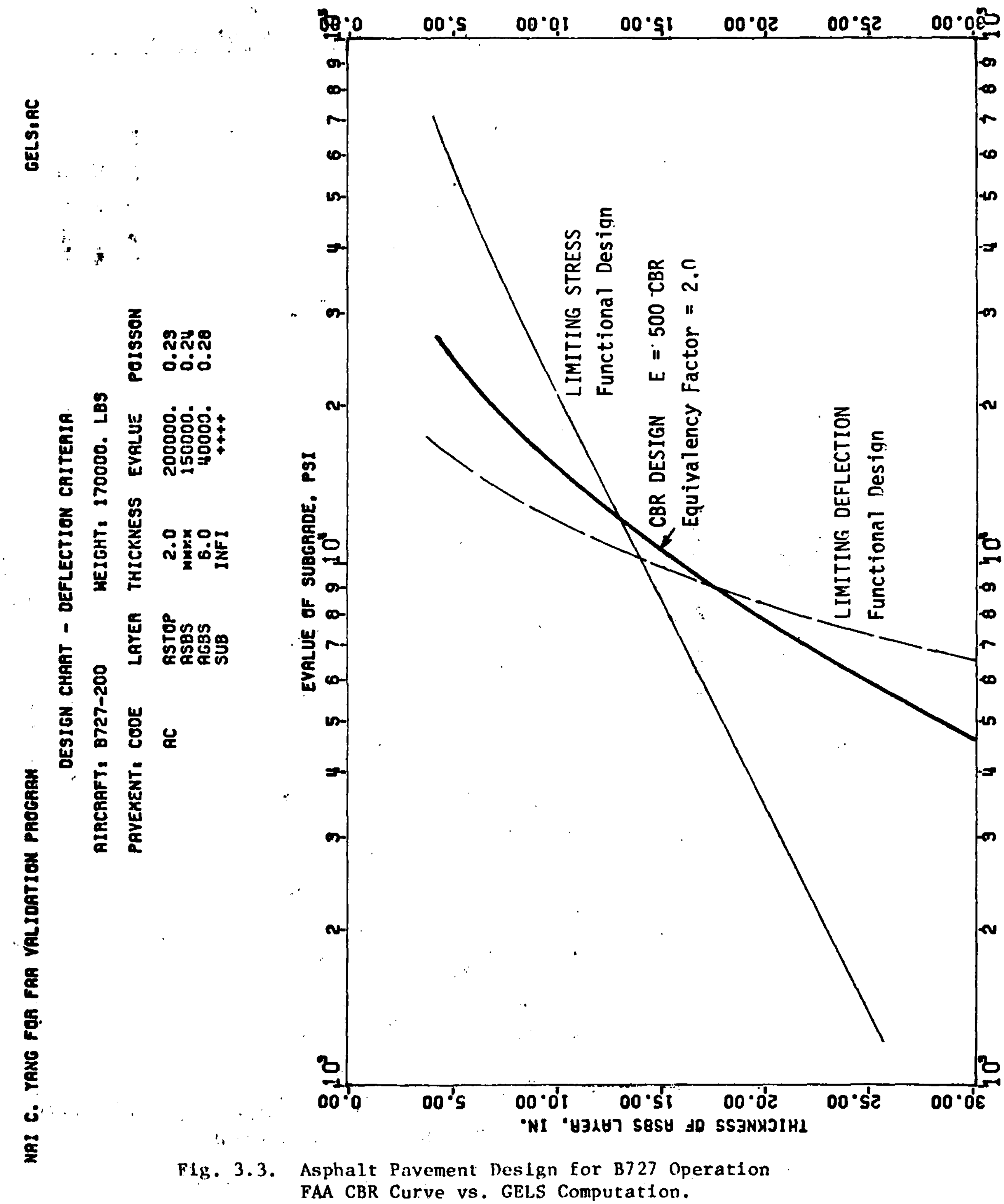


Fig. 3.3. Asphalt Pavement Design for B727 Operation
FAA CBR Curve vs. GELS Computation.

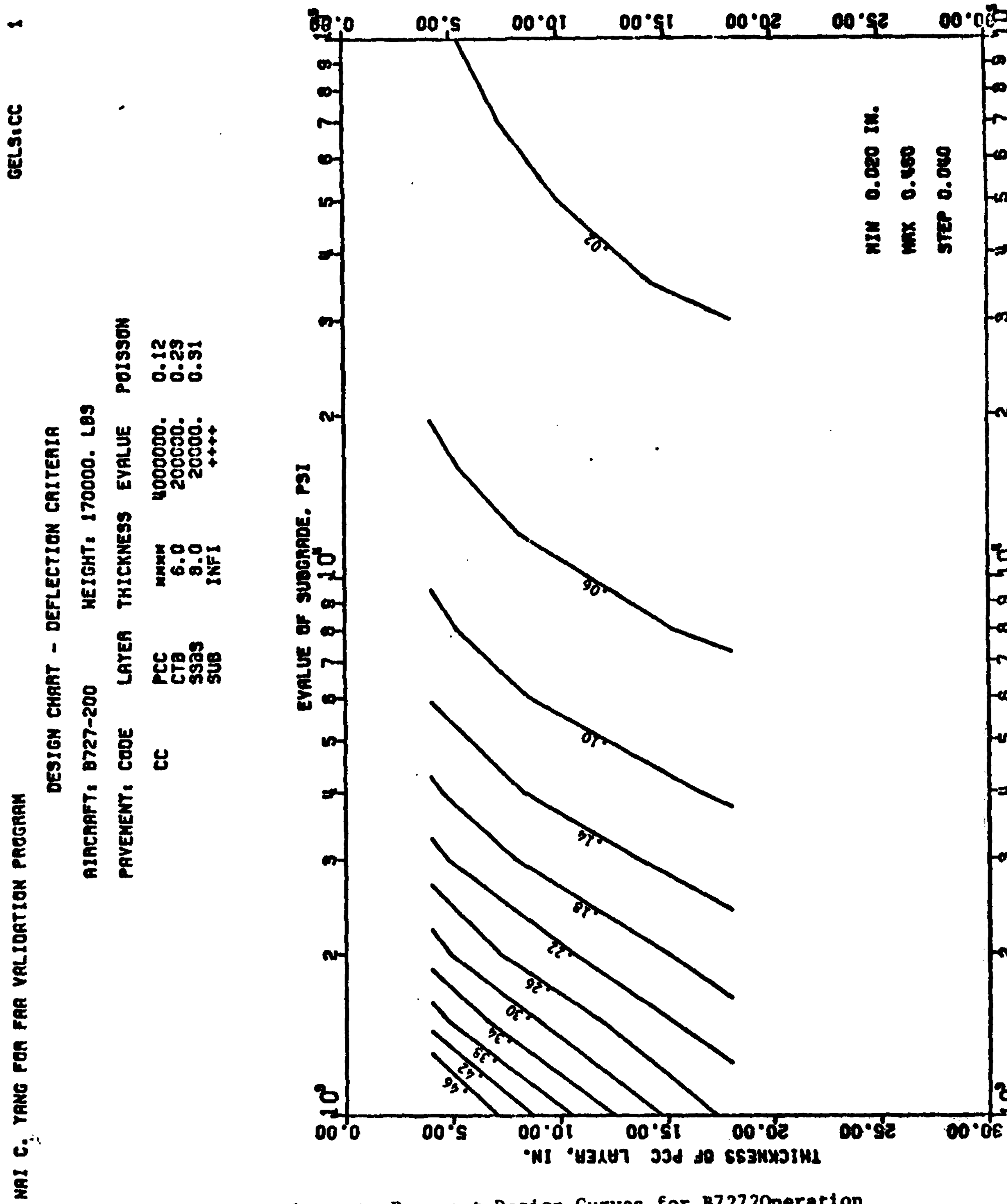


Fig. 3.4. Concrete Pavement Design Curves for B7272Operation Limiting Deflection Criteria.

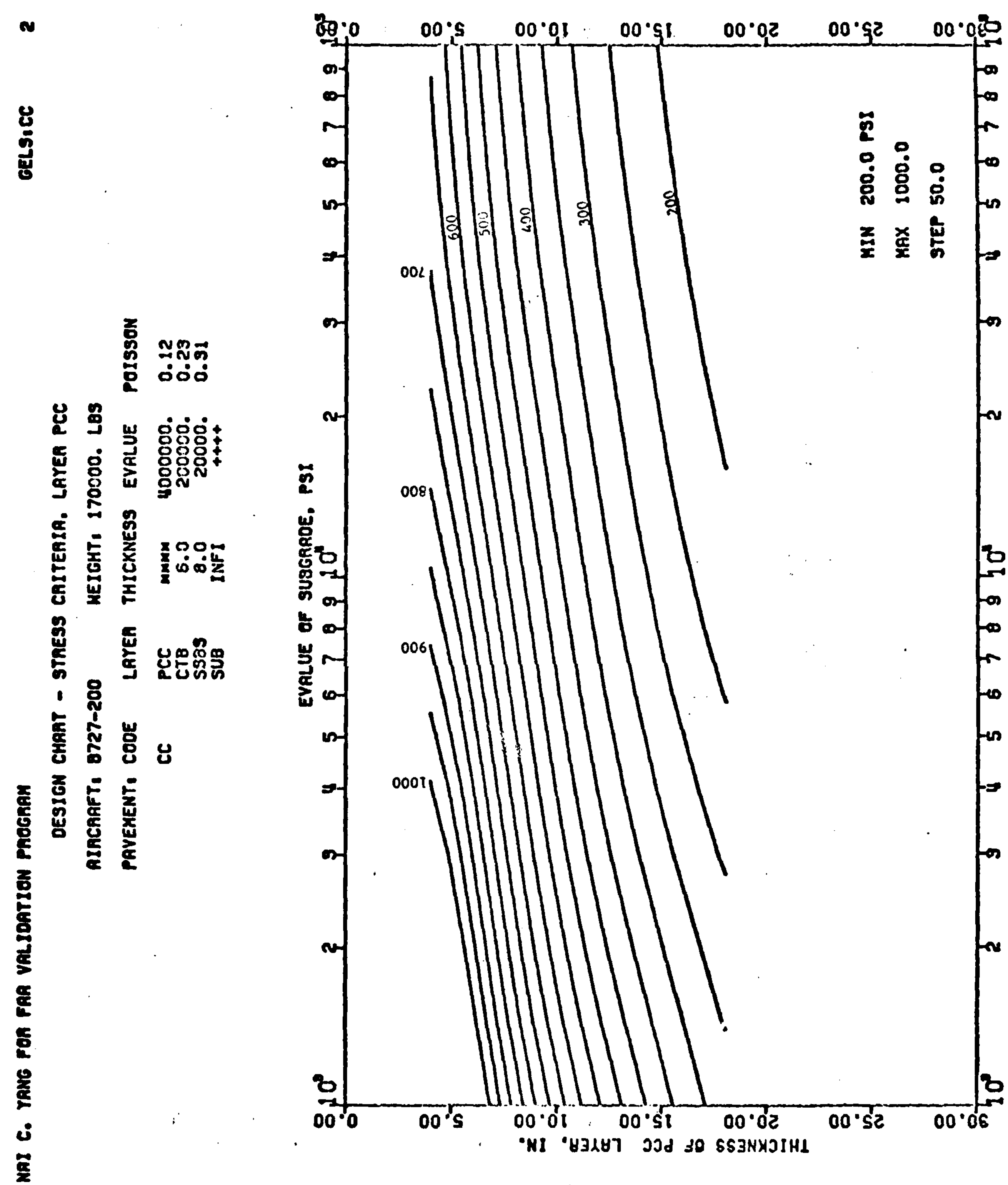


Fig. 3.5. Concrete Pavement Design Curves for B727 Operation Limiting Stress Criteria.

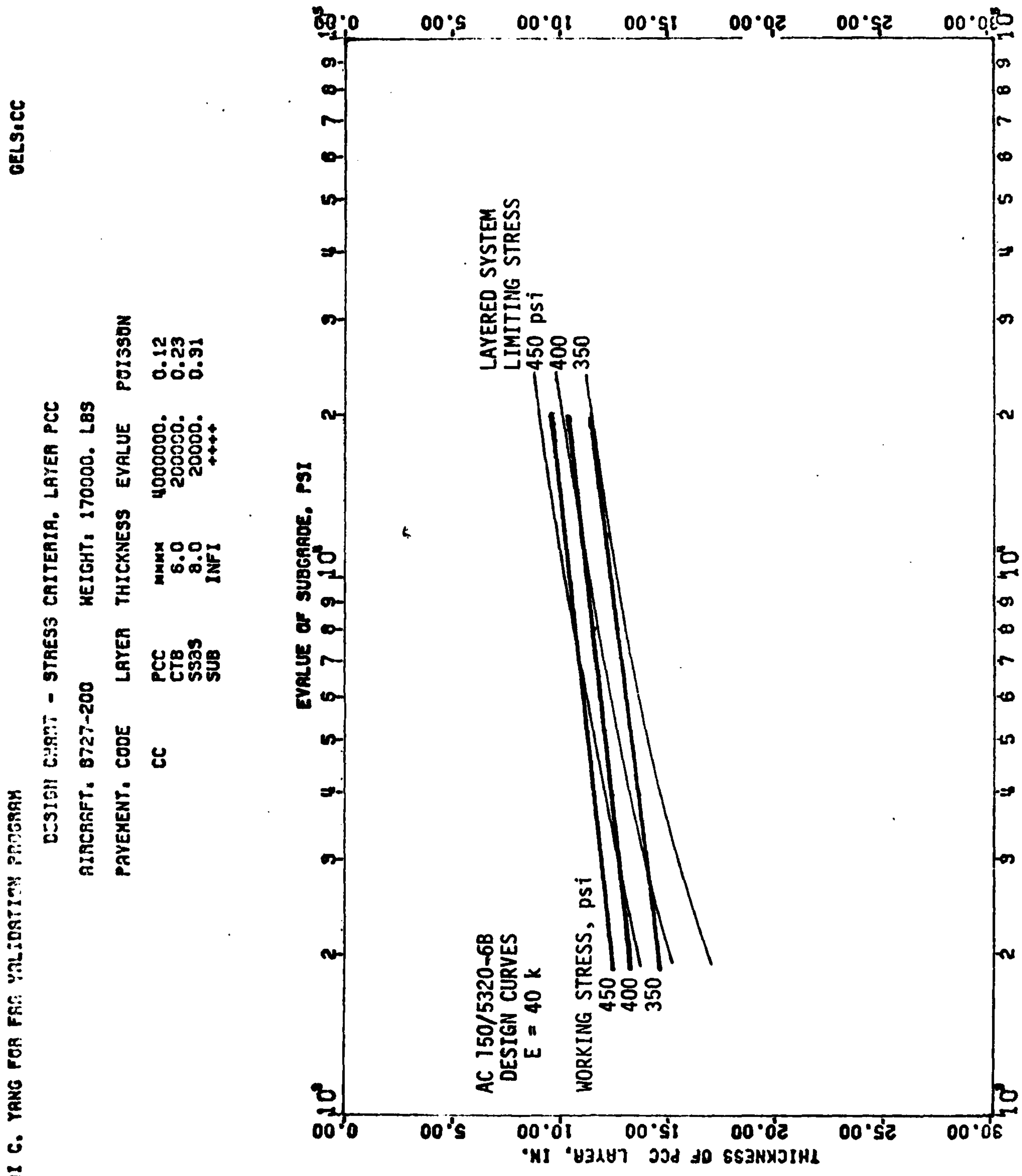


Fig. 3.6. Concrete Pavement Design for B727 Operation
FAA Design Curves vs. GELS Computation.

PART FOUR MATERIAL CHARACTERIZATION FOR PAVEMENT DESIGN AN INTRODUCTION OF UNIVERSAL DATA PRESENTATION

The introduction of the design of functional pavement concept which uses the universal mechanistic method for analysis have increased the demand for a universal characterization of pavement materials. The present material testing methods, such as CBR and k values for subgrade support were developed for special design applications. The sponsorship of such material characterization has inadvertently affected the rational development of universal pavement design method. The principle of mechanistic theory for pavement design should be the layer system equilibrium with respect to stress-strain characteristics of materials The present material testing methods should be modified to reflect the following conditions, such as:

1. All test loads should be of dynamic nature to reflect the time function of moving wheel load;
2. The material response should be a function of load-displacement with reference to time, temperature and confining pressure; and
3. The testing procedure should be universal and applicable to all pavement materials including subgrade soil.

During the FAA validation program, sponsors of selected airports were requested to take undisturbed samples of subgrade soil and pavement materials which were subsequently tested by K. Majidzadeh. The details of this material characterization program are outlined in the following articles.

4.1. SAMPLING AND TESTING PROCEDURE

SAMPLING The procedure for sampling used for this validation program is basically conventional one with emphasis on: (1) prevention of sample disturbance and (2) determination of in-place layer thickness. The following specifications for core and soil samplings are outlined as follows:

1. Conduct core and soil samplings at the specified NDT location.
2. Use NDT location code to identify the samples.
3. Recover portland cement or asphalt concrete layers in full depth by using diamond core drilling of minimum NX size.
4. Drill core samples at moderate speed of rotation with adequate cooling water to prevent breaking of core sample.
5. Record the in-place layer thickness and the actual length of sample.
6. Sample the base and subbase material by conventional spoon and identify the material by standard soil-aggregate classification and penetration resistance.
7. Use no water for any operation below concrete or asphalt pavement layers.
8. Use a thin shell tube, 2" in diameter by 24" long, to extract undisturbed subgrade sample. For sandy soils, the contractor shall submit sampling procedure for approval.
9. Start the first tube sample from a depth 12" below the subbase or base if there is no subbase. The second tube sample shall be five feet deeper. All tube samples shall be 24" in depth.
10. Identify and seal all soil samples in the field. Standard penetration per six inches shall be recorded.

11. Saw all subsoil samples into two 12" sections and store in a strong wooden box. The top section shall be retained by the airport authority and the bottom sections shall be transported to a university laboratory as directed by the airport authority.
12. Clear all sampling operations on active runways and taxiways with the airport tower control. Night operation should be scheduled to prevent interference with aircraft movement.

TESTING The concept of material testing procedure is very similar to NDT frequency sweep method. The dynamic response under full spectrum of forcing function is a realistic reflection on the physical characteristics of pavement materials. The laboratory testing involves the extensive use of modern electro-hydraulic equipment to program the forcing function and also the use of linear variable differential transformer (LVDT) to measure dynamic response in term of displacement of test sample. The calibration factors shall be determined by the monitoring output on a known response system, such as shaker table. The new testing specification is designed for all paving materials including subgrade soils. The specifications of material testings for determining load deflection modulus of soil samples are as follows:

1. Conduct soil classification test, LL, PL, PI and general identification and description of soil samples.
2. Conduct unconfined compressive strength test to obtain a strength estimate of cohesive soil sample.
3. Obtain an estimate of vertical stress in the subgrade under typical aircraft loading.
4. Select a confining pressure representing the in-situ condition under the pavement structure.
5. Select an upper range of vertical stress for testing. For minimal deformation, the vertical stress is about 20 to 30% of the unconfined compressive strength.
6. Conduct each dynamic load test (constant load amplitude) at frequencies of 2, 5, 10, 15, 20, 25, 30, 35 and 40 Hz.
7. Conduct each test at four levels of deviator stress, ranging from 1-5 psi, 5-10 psi, 10-15 psi and 15-20 psi.
8. Document the results of the modulus of elasticity as a function of frequency and deviator stress level.

The testing procedure for portland cement concrete and asphalt concrete is as follows:

1. Determine specimen density and general identification.
2. Conduct unconfined compressive or indirect tensile test.
3. Conduct each dynamic load test at frequencies of 2, 5, 10, 15, 20, 25, 30, 35 and 40 Hz.
4. Select an upper range of vertical stress which does not exceed 25% of compressive strength of the sample.
5. Determine the modulus of elasticity under unconfined condition.
6. Test the effect of temperature on asphalt concrete at 32°F, 50°F, 70°F, 90°F and 110°F. The tests shall be carried out first at low temperature and toward higher temperatures.

7. Use room temperature for testing portland cement concrete.
8. Document test results.

4.2. PRESENTATION OF TEST RESULTS

The testing program, in reality, is an introduction to the research and development on unified material characterization for mechanistic pavement design method. Six test reports have been submitted by Majidzadeh to airport manager at Cleveland, Burlington, Denver, Kansas City, Tampa and Los Angeles. The original test data are available for reference by contacting the author, Majidzadeh, or the manager of the airport mentioned. The data analyses presented herein are confined to the conceptual development and, therefore, the presentation is simplified and generalized.

FREQUENCY SWEEP vs. DYNAMIC MODULUS (SUBGRADE SOIL) All samples are tested under three dimensional (tri-axial) loads. The horizonal loads are constant confining pressure throughout a sequence of frequency sweep test. The vertical load is a programmed semi-sinusoidal force vibrating steadily to obtain a dynamic modulus at one forcing frequency setting. The range of frequency setting under the current test varies from 2 to 40 Hz. The amplitude of the vertical load is a constant during one set of frequency sweep test. A typical example of test result is shown in Fig. 4.1. The E-value of the subgrade soil increases as the forcing frequency of the vertical stress increases. In Tables 4.1 and 4.2, the test results from six airports are summarized for forcing frequency equal to first resonance of NDT.

CONFINING PRESSURE vs. DYNAMIC MODULUS (SUBGRADE SOIL) Under a constant deviator stress at a constant forcing frequency, the relation between confining pressure and dynamic modulus of subgrade soil is similar to those shown in Fig. 4.2. For soil sample at 6 ft depth, the E-value tends to decrease with increasing confining pressure. For soil sample at a depth deeper than 6 ft, a peak E-value may be encountered at a confining pressure, say 10 psi or 20 ft. in depth.

FREQUENCY SWEEP vs. DYNAMIC MODULUS (P.C. CONCRETE) Similar to tests on soil samples, a series of frequency sweep tests was conducted on portland cement concrete core samples. A typical test result is shown in Fig. 4.3. The E-value of concrete sample is not sensitive to forcing frequency from 2 to 20 Hz. It is possible that the natural frequency of portland cement concrete is greater than 200 Hz and the load-creep relationship is not significant during the short loading period.

FREQUENCY SWEEP vs. DYNAMIC MODULUS (ASPHALT CONCRETE) The dynamic modulus of asphalt concrete is very sensitive to temperature and rate of dynamic loading. At temperature 77°F, an example of frequency sweep vs. dynamic modulus is shown in Fig. 4.4. The typical characteristic of this test is that the dynamic modulus increases significantly and continuously with increasing forcing frequency. This can be interpreted to mean that the deflection of asphalt concrete will be significantly decreased at a high speed load application.

TEMPERATURE vs. DYNAMIC STRESS Asphalt concrete is a temperature sensitive material. A typical set of test results is shown in Fig. 4.5. This presentation is selected from a set of tests at forcing function of 8 Hz. The dynamic modulus increases linearly with decreasing temperature on a semi-log plot. With an increase of temperature of 45°F, the dynamic modulus decreases to a level of about 10% of the original value.

DYNAMIC MODULUS vs. YIELD STRESS During the laboratory tests for dynamic modulus of asphalt concrete, measurements to obtain yield stresses were also conducted. The test results are shown in Fig. 4.5. The yield stresses were obtained at a load increment of 330 psi per second. The correlation between the yield stress, σ_y, and dynamic modulus, E, is $\sigma_y = .70 \times \sqrt{E}$ which is in agreement with the original concept of $\sigma_y = s_t\sqrt{E}$ (see Eq. 2.16, Ref. [2]). The standard deviation of individual $\sigma_y / \sqrt{E}$ value is .07. The lower range of reliable correlation is, therefore, $\sigma_y = .65 \times \sqrt{E}$ (see Fig. 4.6). The value of .65 has been used to update the computer default data, STRESS for AC (asphalt concrete). This stress coefficient is very similar to that for portland cement concrete of which the stress coefficient is about 0.40. The process of updating default values will need time and effort but it is an important task in improving the reliability of computer outputs.

4.3. CORRELATION WITH NDT DATA

The primary purpose of the material characterization program is to establish correlation between NDT in the field and material tests in the laboratory. The correlation covered various pavement types at airports in a wide range of climatic conditions. The results are summarized in Table 4.3.

IDENTIFICATION In Table 4.3, each validation test is identified by (1) airport code, such as CLE in column 1 means Cleveland Hopkins International Airport; and (2) facility code and station, such as A31.5 means Runway 5R-23L at Station 31+50.

NDT DATA The data shown in columns 2 and 3 are NDT1 outputs: first resonance frequency and E-value of pavement surface, as shown in processed NDT data file (see p. 90, Ref. [2]).

CORE BORING DATA The data shown in columns 4, 5 and 6 are deduced from the boring logs which were prepared by local soil testing laboratory for the validation airport.

E-VALUES BY LABORATORY TESTS All material samples were tested by Majidzadeh under the unified guidelines specified in this report. The dynamic modulus, in general, is a function of (1) forcing frequency, (2) confining pressure and (3) temperature. The data shown in columns 7, 8 and 10 are selected from the lab results corresponding to a forcing frequency equivalent to the first resonnance, H(1) of NDT (see Fig. 4.1).

The dynamic moduli of asphalt and portland cement concretes are not very sensitive to confining pressure while the dynamic modulus of subgrade soil was selected from the confining condition which corresponds to the sample depth (see Fig. 4.2). The E-values for the base material shown in column 9 are assigned default values according to drainage and moisture conditions at NDT.

E-VALUES COMPUTED BY GELS With reference to the discussions on vibratory force and Eq. 1.23, pp. 10 and 34, Ref. [2], the NDT EPAV value can be converted to surface deflection Wz of existing pavement by

$$Wz = (2pa/EPAV) \times C$$

in which p = unit pressure on test plate, approximately 200 psi;
a = radius of rigid test plate, 9.0 inches in diameter;
C = $\pi/4$ for concrete pavement and 1.0 for asphalt pavement.

The Poisson ratio has no significant effect on the equilibrium of layered system. A default value is computed by

$$\mu = .65 - .08 \log E$$

By utilizing the boring data, lab testings and NDT data presented above, it is possible to convert NDT surface deflection to subgrade E-value (see Fig. 4.7). The mathematical model used is the GELS program. The result of iterative computation is shown in column 11, Table 4.3. The close agreement between data in columns 10 and 11 as shown in Fig. 4.8 suggests that:

1. The concept of NDT and new material characterization method are compatible with mechanistic pavement analysis utilizing the general equilibrium of layer system, GELS.
2. In GELS computation, the thickness of existing pavement layer is much more sensitive than its E-value in determining ESUB. For example, a small variation in E-value of concrete material will have no significant effect on the computed thickness of concrete layer by GELS program.
3. The thickness of asphalt concrete, on the other hand, depends primarily on the reliability of subgrade E-value as well as the dynamic modulus of paving materials. For example, a small variation of subgrade E-value may have a noticable influence on computed thickness of asphalt layer.
4. There are discrepancies between these test results. The error and mistake in the field as well as in the laboratory should be reviewed.

Table 4.1 Dynamic Modulus of Subgrade Soil
Los Angeles International Airport

Facility	NDT No.	H(1) Hz	Depth ft.	σ_3 psi	E-value under Deviatoric Stress, psi 1.62	2.04	2.44	3.25	4.06	4.87	6.09
RW 25R	A19.0	9.05	2.33	0.				6800			9800
				20.			2400	6600			10800
				30.			2800	7200			10500
			5.00	20.	3400			3700			4500
				30.	4500			4500			5300
				40.	4700			5100			5500
RW 25R	A96.0	8.05	1.70	20.	1500			3300			6100
				30.	1700			3400			4300
				40.	2100			3700			6000
			4.00	20.	3400			3600		4700	
				30.	4200			4300		4900	
				40.	4300			4500		5100	
RW 25L	B21.0	9.05	1.50	20.	2600			4900			5800
				30.	3000			4100			6200
				40.	3200			4400			6500
			3.00	0.	2500			2300			2100
				20.	1900			2300			3000
				30.	2400			2700			2900
			5.00	0.	3400			3400			3200
				20.	3600			3400			3300
				30.	3600			3300			3400
RW 25L	B104.	8.04	1.50	20.	2100			2100			4700
				30.	900			2900			3300
				40.		2300			3500		4400
			4.00	20.	4300						
				30.	6200			6300			6600
				40.	5800			9300			9300
RW 24L	C75.0	8.04	2.00	20.	2900		3700				
				30.	2300		2400				
				40.				2700			4000
			5.00	20.	2100			3600			3900
				30.	3000			3700			4700
				40.	3500			4600			5400
RW 24L	C96.0	9.06	2.00	20.	5200			5700			
				30.	4800			5200			
				40.	5200			5800			5600
			5.00	0.	4200			4600		4900	
				20.	4600			4700		5300	
				30.	4600			4800		5500	

Table 4.2 Dynamic Modulus of Subgrade Soil at Five Civil Airports

Facility	NDT No.	H(1) Hz	Depth ft.	σ_3 psi	E-value under Deviatoric Stress, psi 1.0+	3.0+	5.0+	10.+	15.+	20.+	30.+
Cleveland											
RW 5R	A31.5	10.1	5.0	10.				25500	20400	18800	15400
	A40.5	8.99	9.1	10.			6000	6300	6700	7600	
	A52.5	8.97	4.2	0.			5900	5600	5100	4300	
			8.9	10.			16300	14800	11900	10600	10100
	A58.5	9.00	3.6	0.			8000	8900			
				10.			5500	5600	5800	6600	
				20.					6200		
	A69.5	11.0	3.7	10.				21500		13700	12500
	A77.5	10.9	4.1	10.			7000	7400	7400	8000	
	A83.5	11.0	4.5	10.				12400		12600	14000
	A89.5	11.0	7.0	10.			7200	8000			
RW 18R	C20.5	10.0	4.5	10.				17400	18000		
TW O	J03.5	8.90	5.5	10.			4800	5900	6900		
Kansas City											
TW C	D01.6	8.98	6.0	10.			10400	8300	6700		
	D03.7	9.02	3.0	10.			12100	15000	13100	12200	10500
				10.			22800	24100	23700	21600	17100
	D05.7	8.98	6.0	10.			19700	15300	11200	9900	7600
Denver											
RW 8L	H108.	8.99	2.5	10.			12600	10300	9300		
	H142.	9.97	4.5	10.			25300	25000	24500	25300	
				10.			11200	11200	10900	11400	10600
				10.			22000	23200	22200	22400	
TW C	I051.	9.96	5.0	10.			15200	15100	15400		
				10.		14400	16800	13400			
				10.		20800	19800	20800			
Tampa											
TW G	H082.	10.1	3.0	10.	3100		6000	9800			
				15.	2400		4600	6100			
				20.	2300		4900	8900			
			9.0	10.	3000		4300	5000			
				15.	3300		4000				
				20.	3400		3800				
TW J	I056.	9.07	5.0	40.	3200		4200				
TW R	N106.	9.03	4.0	20.	1600	3900	5500				
				30.	1400	4200	5600				
Burlington											
RW 15	A15.0	7.99	Froz	10.	470000	420000	270000		220000		
TW A	C20.0	7.98	5.0	10.		23600	20400	23000	21100	21600	22700

TABLE 4.3 SUMMARY OF NDT, BORINGS, LAB TESTS AND ESUB COMPUTATION

ID	NDT DATA		BORING DATA			E-VALUES BY LAB TEST				COMPUTED
TEST	H(1)	EPAV	AC	CONC	BASE	AC	CONC	BASE	ESUB	ESUB
	Hz	psi	in.	in.	in.	ksi	ksi	ksi	psi	psi
1	2	3	4	5	6	7	8	9	10	11
CLE										
A31.5	10.1	142439.	5.0	9.2	11.2	400.	4000.	40.	25500.	24710.
A40.5	9.0	47927.	3.5	10.2	11.5	400.	4000.	40.	6000.	4409.
A52.5	9.0	80864.	4.2	8.7	18.8	400.	4000.	30.	11100.	10500.
A58.5	9.0	70290.	4.2	8.7	14.0	400.	4000.	40.	8000.	8276.
A69.5	11.0	93291.	5.0	9.2	13.9	400.	4000.	40.	21500.	12066.
A77.5	10.9	121241.	5.2	9.2	19.6	400.	4000.	40.	7000.	15357.
A83.5	11.0	94927.	4.2	9.5	12.1	400.	4000.	40.	12400.	11649.
A89.5	11.0	126973.	4.5	10.6	11.9	400.	4000.	40.	8000.	17491.
C20.5	10.0	119199.	4.2	10.2	12.0	400.	4000.	40.	17400.	16782.
J03.5	8.9	31940.	6.0	3.0	8.6	400.	4000.	40.	4800.	5560.
KCI										
D01.6	9.0	62177.	0.0	10.0	6.0	0.	4300.	40.	10400.	11343.
D03.7	9.0	92137.	0.0	10.0	6.0	0.	3600.	40.	22800.	23200.
D05.7	9.0	86463	0.0	10.0	6.0	0.	4300.	40.	19700.	19307.
DEN										
H108.	9.0	56629.	0.0	12.0	8.0	0.	3000.	40.	12600.	9342.#
H142.	10.0	106187.	20.0	0.0	16.0	540.	0.	40.	19500.	20431.#
I051.	10.0	67327.	0.0	12.0	8.0	0.	3000.	40.	16800.	11723.#
TPA										
H082.	10.1	68154.	0.0	12.0	15.0	0.	4700.	10.	6000.	10742.#
I056.	9.1	150136.	0.0	16.0	8.0	0.	4600.	50.	4200.	22942.#
N106.	9.0	144891.	0.0	18.0	18.0	0.	4500.	13.	5500.	21505.#
BTV										
D27.5	6.9	18975.	3.0	0.0	18.0	200.	0.	30.	23100.*	4680.
C20.0	8.0	42098.	3.0	8.0	12.0	200.	3000.	30.	23600.*	7512.
A00.5	10.0	179537.	0.0	17.0	12.0	0.	4600.	30.	22800.*	28089.
A15.0	8.0	36383.	7.0	0.0	18.0	200.	0.	30.	23000.*	11453.
LAX										
A19.0	9.1	88430.	0.0	12.0	8.0	0.	4800.	100.	9800.	13961.
A96.0	8.1	37865.	3.0	0.0	22.0	1000.	0.	100.	6100.	4566.
B21.0	9.1	91341.	0.0	15.0	8.0	0.	4800.	100.	5800.	11662.
B104.	8.0	31472.	3.0	0.0	12.0	1000.	0.	100.	4700.	5860.
C75.0	8.0	52071.	10.0	0.0	12.0	1000.	0.	100.	4000.	5875.
C96.0	9.1	83737.	0.0	15.0	28.0	0.	5700.	20.	5600.	5876.

* Tests on compacted sand samples in the laboratory.
# Exact thickness of core samples are not shown in boring log.

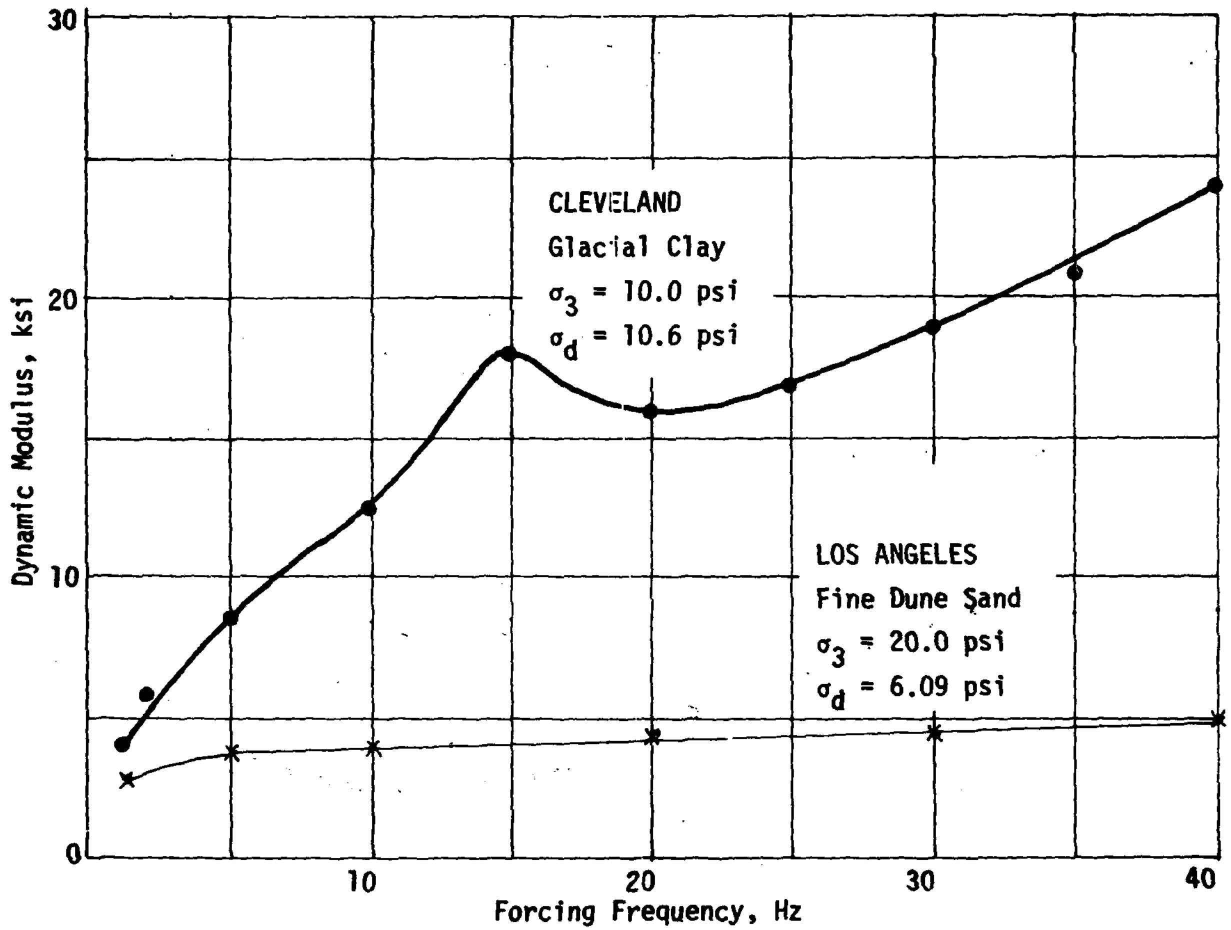


Fig. 4.1 Effect of Forcing Frequency on Dynamic Modulus of Subgrade Soil

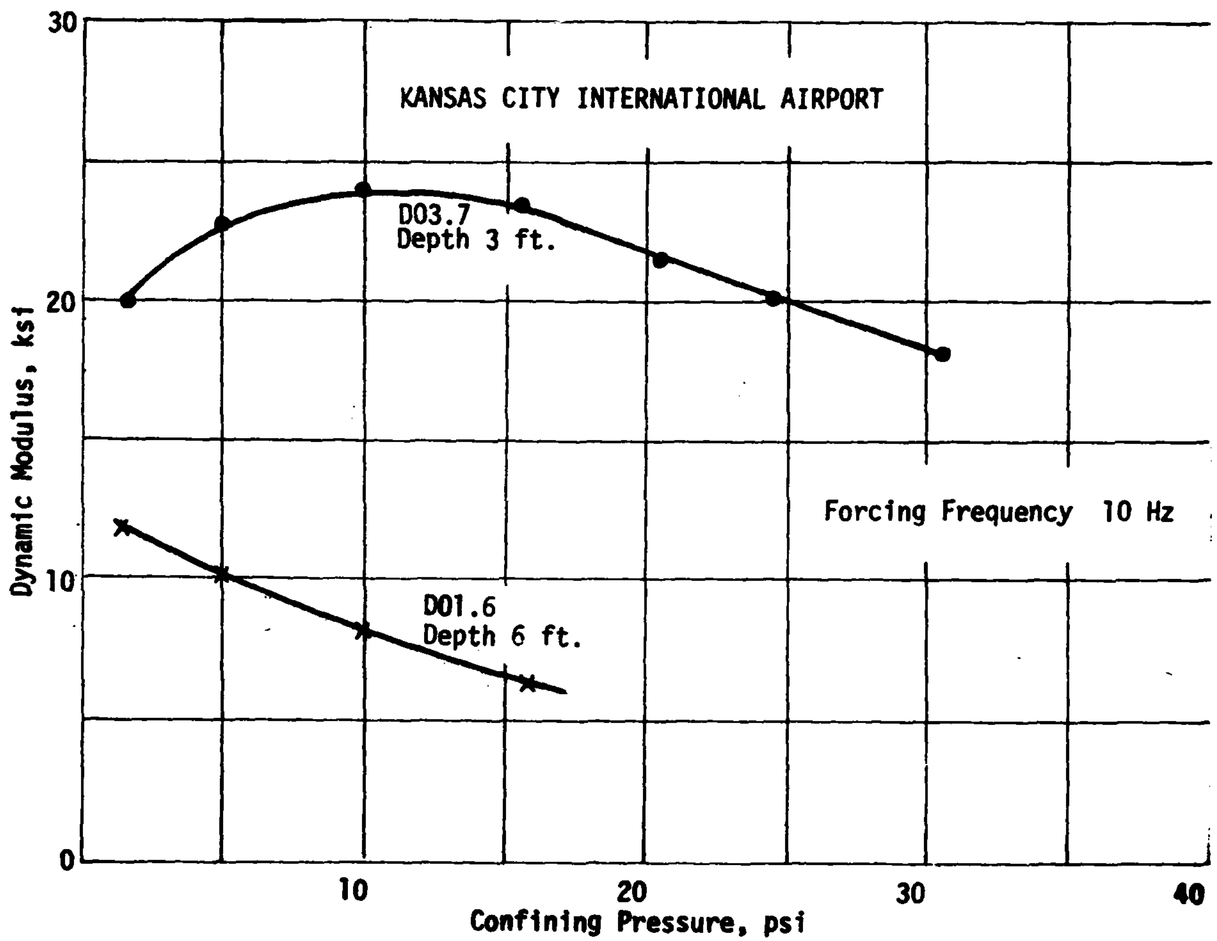


Fig. 4.2 Effect of Confining Pressure on Dynamic Modulus of Subgrade Soil

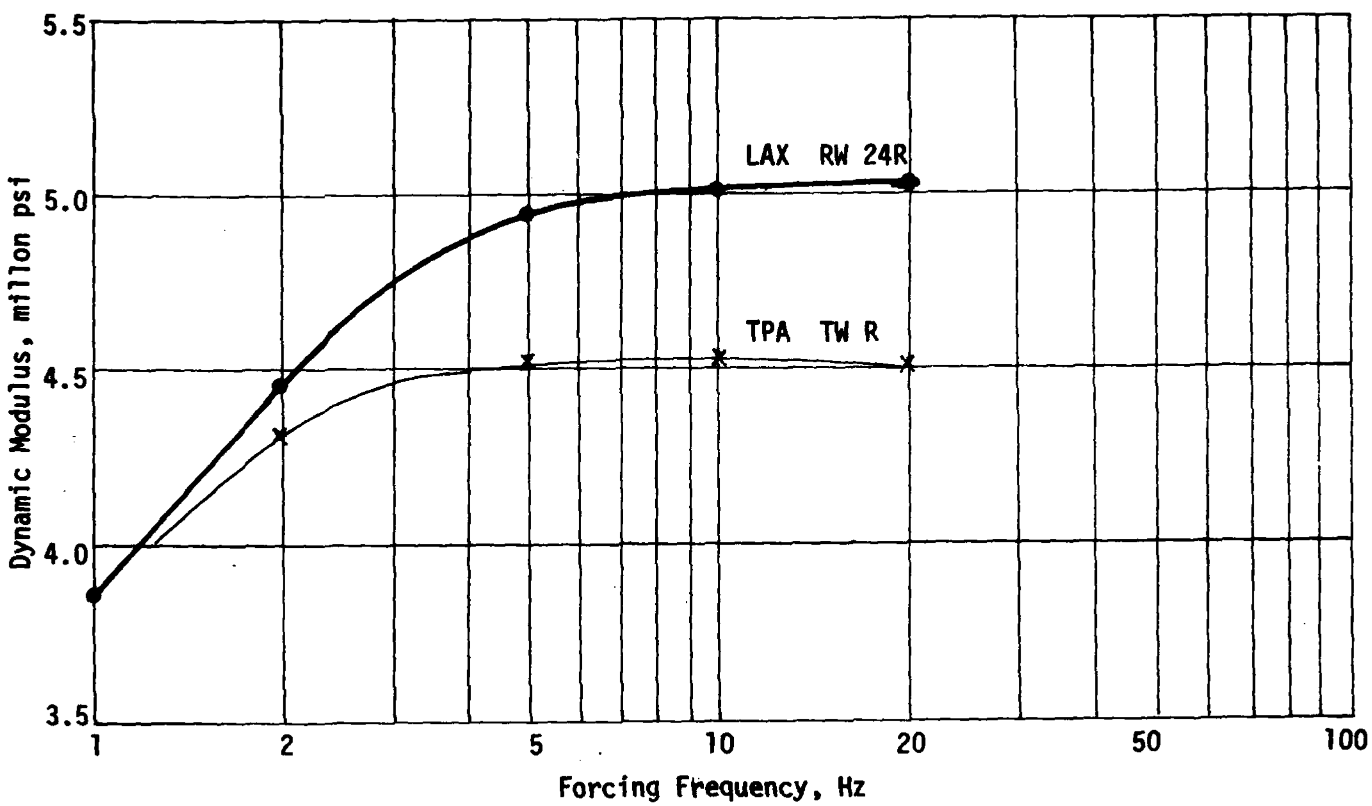


Fig. 4.3 Effect of Forcing Frequency on Dynamic Modulus of Portland Cement Concrete

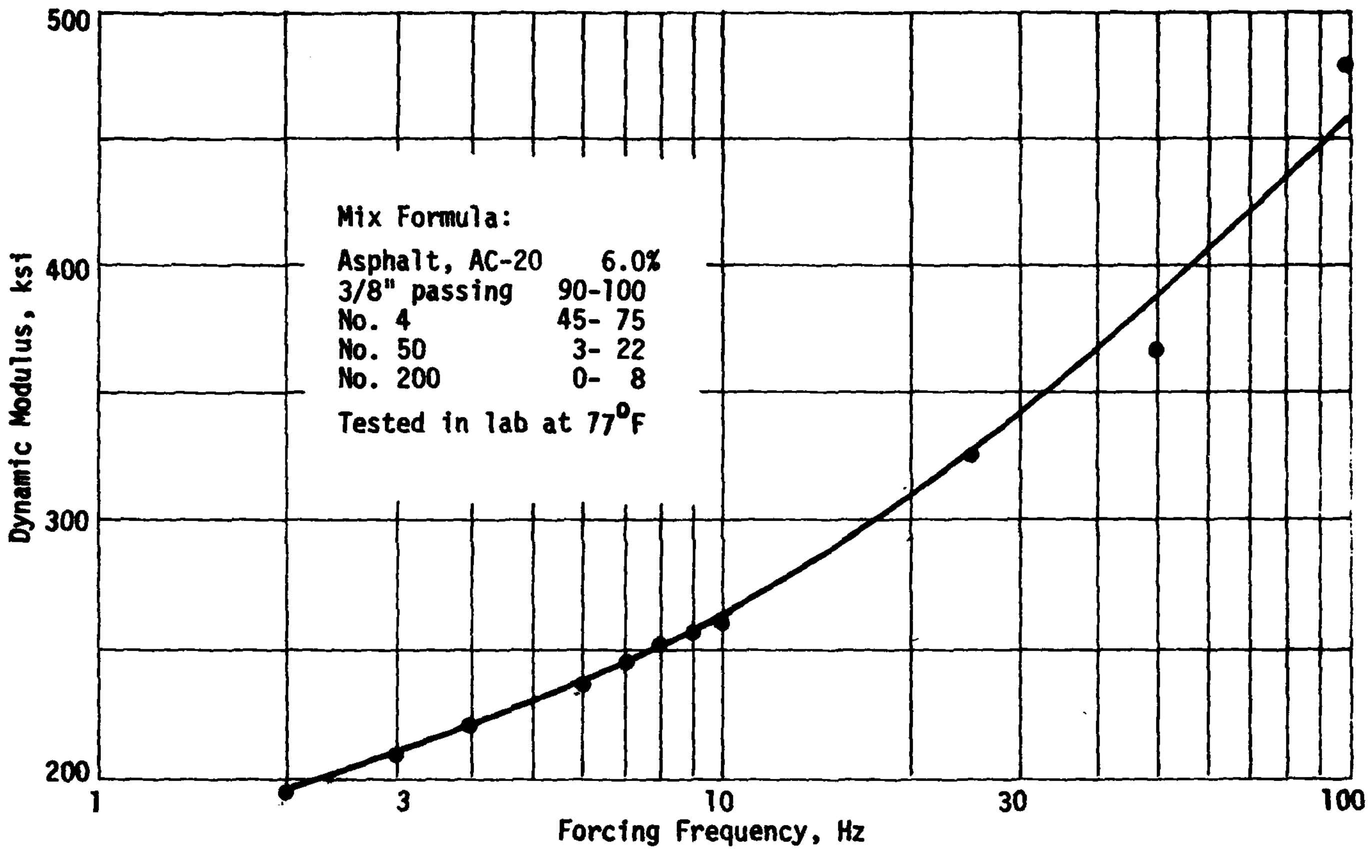


Fig..4.4 Effect of Forcing Frequency on Dynamic Modulus of Asphalt Concrete

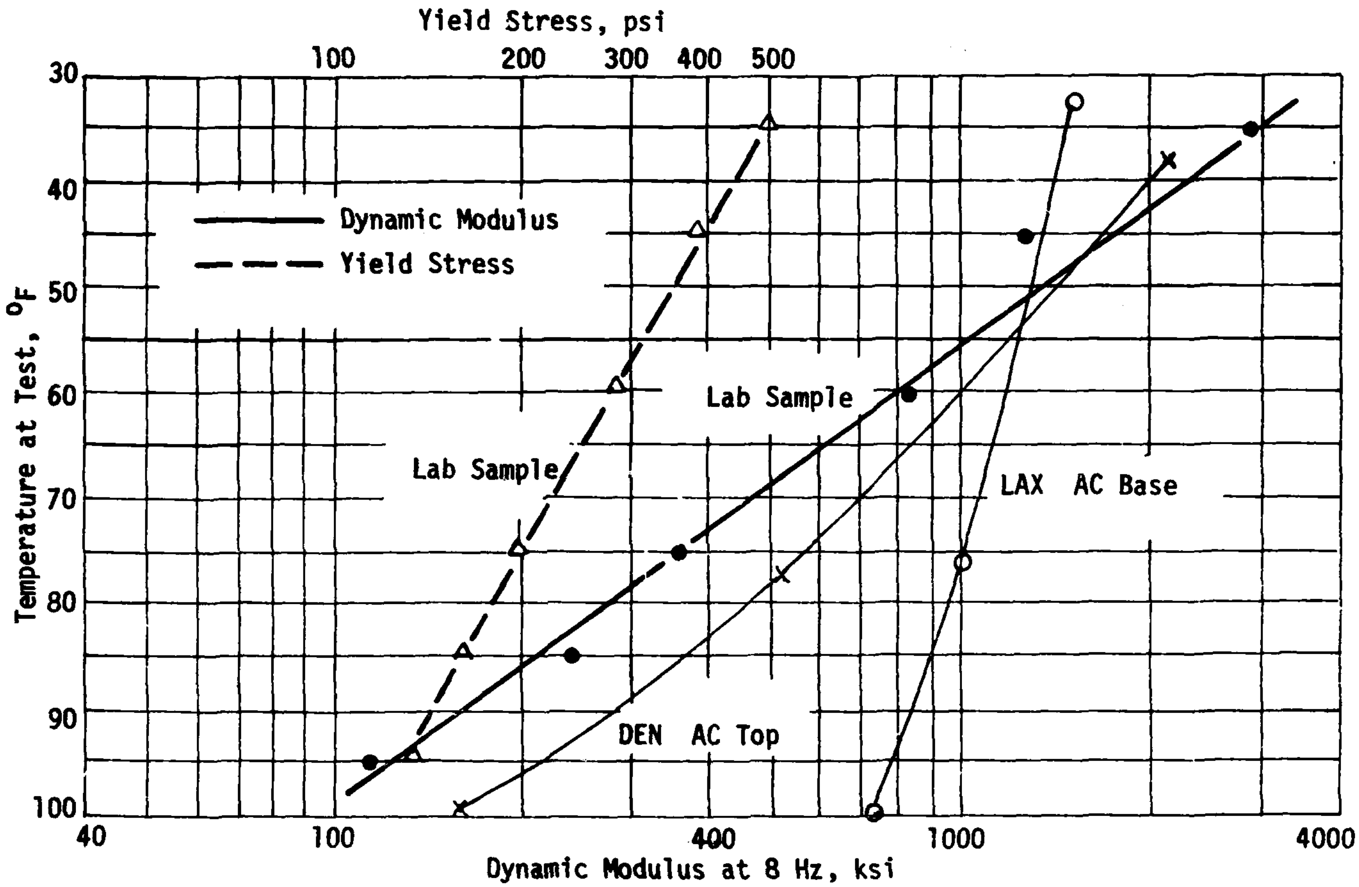


Fig. 4.5 Effect of Temperature on Dynamic Modulus and Yield Stress of Asphalt Concrete

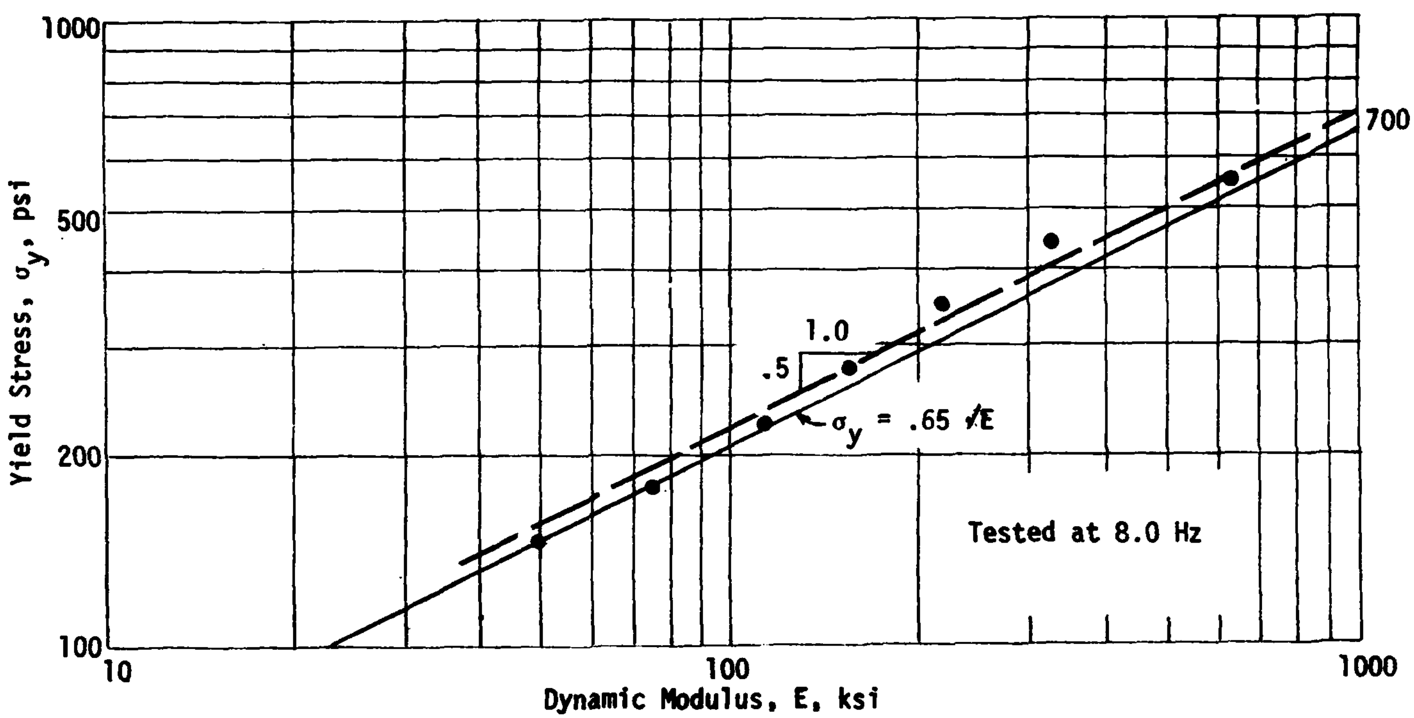
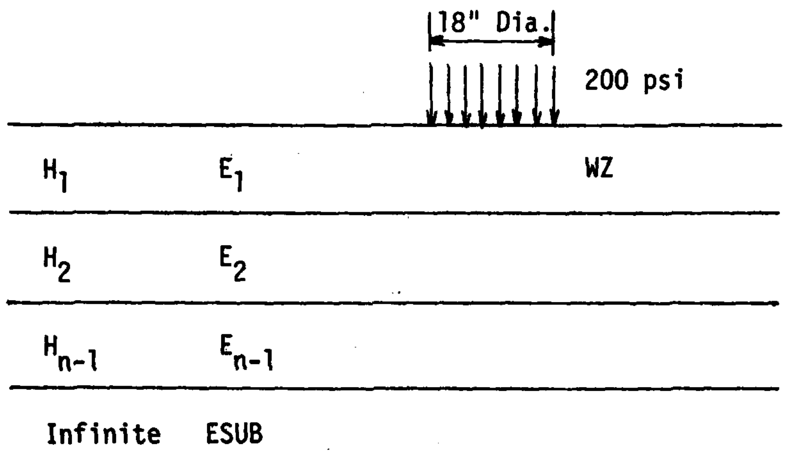
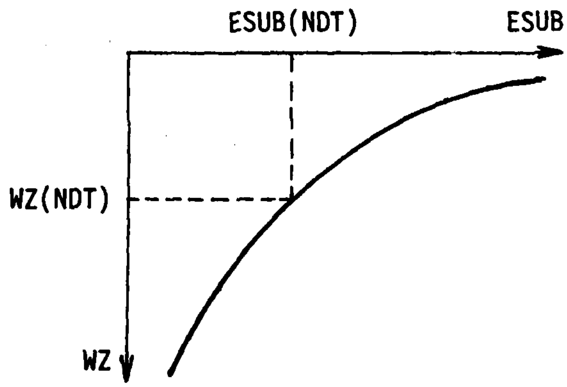


Fig. 4.6 Correlation of Dynamic Modulus and Yield Stress of Asphalt Concrete

Fig. 4.7 NDT3 Operation Procedure for Determining Subgrade E-value

1. Establish type of existing pavement in terms of E-values and thickness.
2. Compute surface deflection, WZ, under a single load by GELS.
3. Plot WZ/ESUB design chart.
4. Convert EPAV(NDT) to surface deflection WZ(NDT) by following equation WZ(NDT) = 3600/EPAV(NDT) x C, in which C-value is 1.00 and 0.62 for asphalt and concrete pavement respectively.
5. Determine ESUB(NDT) from design chart by computer.





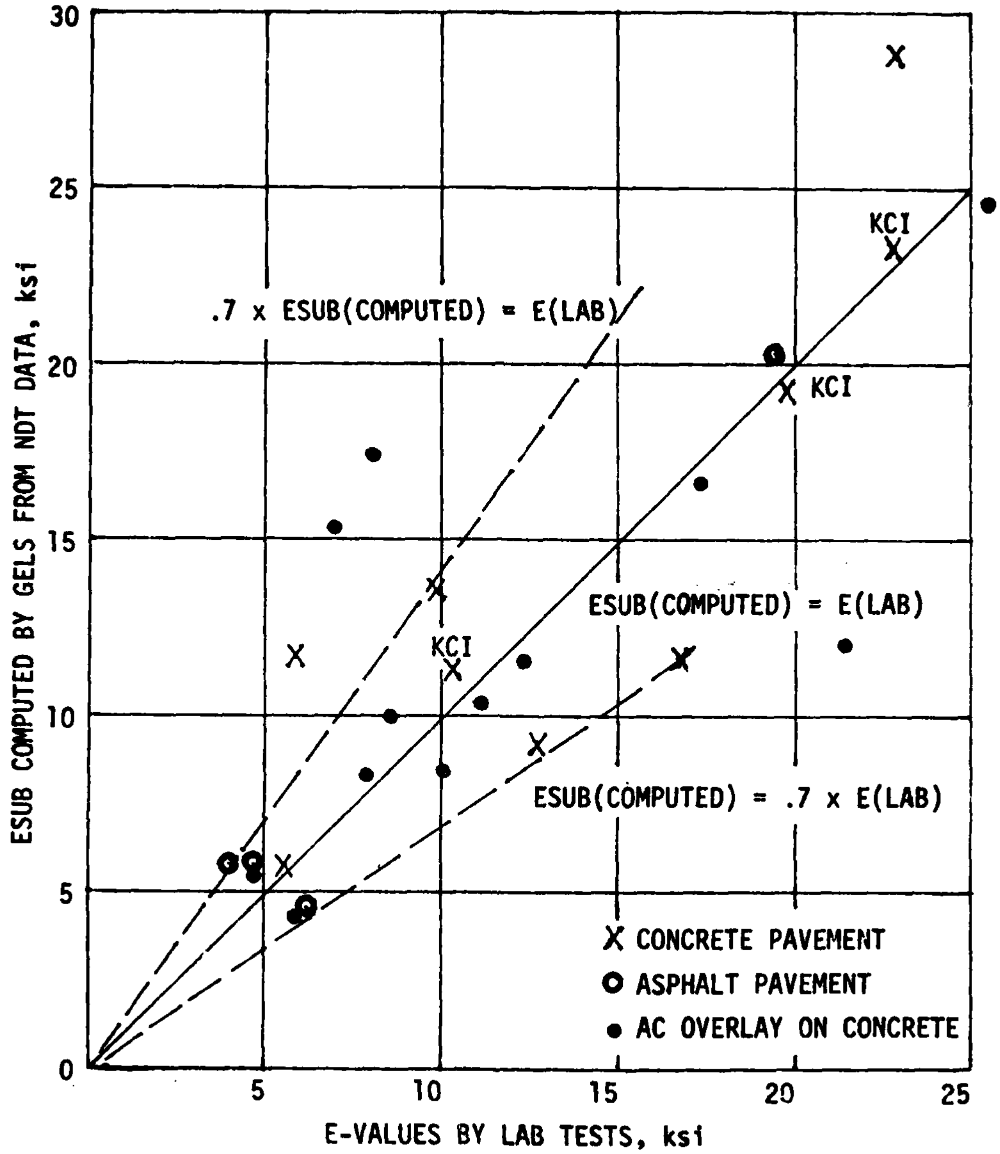


Fig. 4.8 Correlation between E-values by Lab Tests and Computed ESUB from NDT Data

PART FIVE FUTURE PROGRAMS

The nondestructive evaluation and functional pavement design were orginally developed to meet the construction needs of New York Airports and subsequently refined during applications at many hub airports. Because it is intended for practical application, many academic theoreticians may consider that the NDT - functional concept should be elaborated in greater detail. On the other hand, many practicing engineers who have been accustomed to designing pavement mainly by using empirical design charts find that the NDT - functional concept and computer automation appear too complex for ready interpretation. This report provides the necessary information to use the complete system from conducting NDT to determining the cost-benefit of ten different pavement designs. However, the following future programs may be conducted to provide added features to the system:

MATERIAL CHARACTERIZATION A unified material characterization has been introduced in this report. It may be desirable to establish a realistic listing of the characteristics of materials in each FAA region, particularly, the physical properties of materials treated with asphalt in the southern part of the United States.

COMPUTER SIMULATION Within the framework of GELS, supplemented by other basic mathematic models such as finite element method, a simulation analysis may be performed to reduce the dependence on default values and the uncertainties in user's inputs.

VIBRATION-SMOOTHNESS CRITERIA AND PROGRESSIVE DEFORMATION These work items as outlined in Ref. [2] may be considered with the cooperation of the Industry Working Group.

FINALLY The result of this validation study should be incorporated in Ref. [2] which will be used as the source reference.

REFERENCES

1. Yang, Nai C., Design of Functional Pavements, McGraw Hill Book Co., New York, 1972.
2. Yang, Nai C., Nondestructive Evaluation of Civil Airport Pavements, FAA-RD-76-83, September 1976.
3. Heukelom, W. and Foster, C. R., Dynamic Testing of Pavements, ASCE Trans., Vol. 127, pp.425-457, 1962.
4. Crawford, J. E., Hopkins, J. S. and Smith, J., Theoretical Relationships between Moduli for Soil Layers beneath Concrete Pavements, FAA-RD-75-140, May 1976.
5. Crawford, J. E. and Katona, M. G., State-of-the-Art for Prediction of Pavement Response, FAA-RD-75-183, September 1975.
6. Yang, David, Response of Multi-Frequency System, MS Thesis, Massachusetts Institute of Technology, June 1978.
7. Houbolt, H. C., Runway Roughness Studies in the Aeronautic Field, Trans. ASCE, vol. 127, pp. 427-447, 1962.

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APPENDIX 1 SEMINAR NOTES ON NDT EVALUATION AND DESIGN OF FUNCTIONAL PAVEMENTS

CONTENTS

SESSION 1

NDT THEORY AND DATA PROCESSING

General Equation of Forced Vibration

Newton's Law of Motion:

$$(k - m\omega^2)\ z \sin(\omega t - \phi) - c\omega z \sin(\omega t - \phi + \pi/2)$$
$$= - F_o \sin \omega t$$

$$z^2 = F_o^2 / [(k - m\omega^2)^2 + (c\omega)^2]$$

$$= F_o^2 / k^2[\{1-(\omega/p)^2\}^2 + (2\beta\omega/p)^2]$$

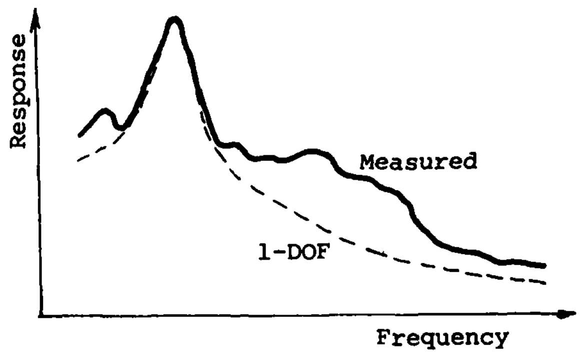
WES Study (FAA RD-76-158)

Dynamic Frequency Response Spectrum Method

$$|z(\omega_i)|^2 = F^2/k^2\ [\{1-(\omega_i/p)^2\}^2 + (2\beta\omega_i/p)^2]$$

p = Constant for one degree of freedom.

Conclusion by R. A. Weiss: Inadequate Response



Multi-Degree of Forced Vibration

1. Constant forcing amplitude, F
2. Multi-frequency of forcing function, ω_i
3. Multi-degree of response system, p_j

   i, j are counters.

$$|z(\omega_i)|^2 = F^2 \sum^{j} 1/k_j^2 \, [\{1-(\omega_i/p_j)^2\}^2 + (2\beta\omega_i/p_j)^2]$$

An unique solution can be obtained when $i = j$, the required number of test, i, is equal to the number of response system, j; and solve i-th number of simultaneous equations.

Actual Conditions:

1. The number of response systems, j, is unknown.
2. The number of tests and frequency intervals are an arbitrary assignment.

There can be no unique solution.

David Yang, Ref. [6] (see p. 90), assumes $j \neq i$

His analysis indicates:

1. The summation of response square $|z(\omega_i)|^2$ depends on the number of tests, i.e. the number of response systems and the frequency interval of NDT.
2. An unique solution can be obtained for multi-degree, but discrete, response system such as bridge structure.

Spectrum Density Approach

1. Measuring peak response at each forcing frequency, ω_i.
2. Major response at a given forcing frequency is derived from the response system having its natural frequency p_j equal to ω_i.
3. Forcing frequency, ω_i, can be expressed by $u = \omega_i/p_1$ in which p_1 is response function at the maximum peak response of all tests. i.e., first resonance of forced vibration.
4. Let $|z(u)|^2 = |z(\omega_i)|^2$

   and $|x(u)/k|^2 = \overset{j}{\Sigma}\ 1/k_j^2 |\ (1-(\omega_i/p_j)^2)^2 + (2\beta\omega_i/p_j)^2|$

   Therefore $|z(u)|^2 = F^2|x(u)/k|^2$

   or $\pm\ z(u) = F\ x(u)/k$

---

z(u) is measured peak response at steady state of vibration of forcing frequency ω_i/p_1 and represents the spectral density of that frequency. Displacement lags can be neglected.

5. Mathematically, summation of spectrum density $z(u)\Delta u$ is a constant when spectrum interval Δu is modified in term of forcing frequency u.

$$\frac{1}{F}\int_1^\infty z(u)\ .\ \frac{du}{u} = \frac{1}{k}\int_1^\infty x(u)\frac{du}{u}$$

$$= \frac{1}{2k}\ln\frac{1+\beta}{\beta}$$

or $k = \frac{1}{2}\ln\frac{1+\beta}{\beta}\ .\ \dfrac{1}{\frac{1}{F}\int_1^\infty z(u)\ .\ \frac{du}{u}}$

6. For plate load test on elastic system

$$k = \frac{P}{W_o} = \frac{\pi aE}{2(1-\mu^2)}\ .\ \frac{1}{CF_w}$$

7. E-value by NDT Process

$$E = \frac{1}{2a} \cdot \frac{1}{\frac{1}{2F} \int_1^\infty z(u) \cdot \frac{du}{u}} \cdot \frac{1 - \mu^2}{\pi} CF_w \ln \frac{1+\beta}{\beta}$$

$C = 1.0$ for flexible plate

$C = \pi/4$ for rigid plate

$F_w = 1.0$ for one layer system

μ ranges from .25 to .40

β ranges from .02 to .05

$\frac{1 - \mu^2}{\pi} CF_w \ln \frac{1+\beta}{\beta}$ ranges from .85 to 1.17

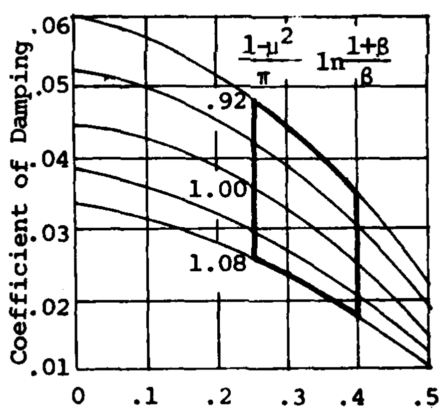
common range .95 to 1.05

Simplified Equation:

$$E = \frac{1}{2a * SUMZ}$$

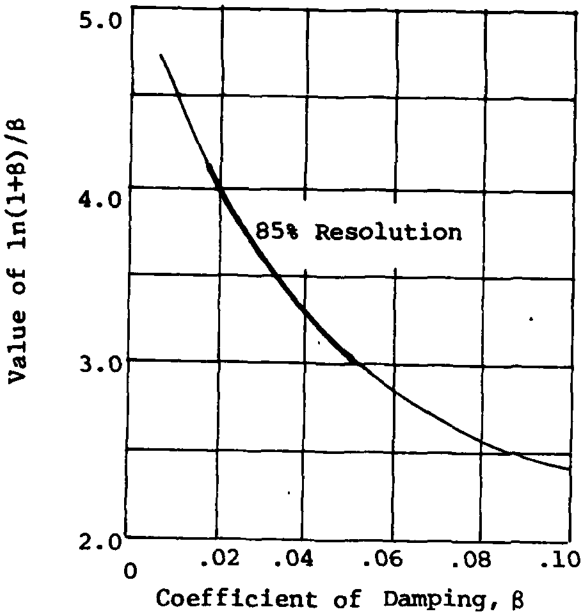
SUMZ = Quasi-static load deflection

$$= \frac{1}{2F} \int_1^\infty z(u) \cdot \frac{du}{u}$$



Error Analysis

	Range of Reliability	Most Reliable
Processed NDT E	$\bar{E}$ to $\bar{E}$ $(1-\nu)$	$\bar{E}$ $(1-\nu)$
Poisson's Ratio	.25 to .40	
Damping Coefficient	.02 to .05	
Logarithmic Decrement	.10 to .30	



Effect on Damping on E-value Computation

Computer Processing

Subroutine NDT 1 Data Processing

$$SUMZ = \int_1^\infty \frac{z(u)}{2F} \cdot \frac{du}{u}$$

$$= \frac{z(1)}{2F(1)} \cdot \frac{H(2) + H(1)}{2\,H(1)}$$

$$+ \sum_2^{n-1} \frac{z(I)}{2F(1)} \cdot \frac{H(I+1) - H(I-1)}{2\,H(I)}$$

$$+ \frac{z(n)}{4F(n)}$$

Computer Plotting:

$$\frac{z(I)}{F(I)} \text{ vs } H(I)$$

H(I) = Forcing frequency at test

$\frac{z(n)}{4F(n)}$ = Tail area

z(1) = Peak response at 1st resonance.

Subroutine NDT 2 Statistical Process

Mean Value: $\bar{x} = \sum^{n} x/n$

Standard Deviation:

$$SDEV = \frac{1}{n-1} \cdot \sum^{n} (x - \bar{x})^2$$

Area E-value:

$$E\text{-}AREA = (\bar{x} - SDEV)$$

Computer Plotting:

x and E-AREA

In the future,

NDT 1 will be programmed in testing machine, and

NDT 2 will remain valid for statistical processing.

Subroutine NDT 3

Determine Subgrade E-value by GELS, General Equilibrium of Layered System

Step 1. Determine composition of existing pavement

Layer	Thickness	E-value	Poisson's Ratio
1	h_1	E_1	μ_1
2	h_2	E_2	μ_2
n-1	h_{n-1}	E_{n-1}	μ_{n-1}
n	h_n	E_n	μ_n

From construction record:

Determine h_1, h_2 ..... h_{n-1} $h_n = \infty$ subgrade

Assign default values:

E_1, E_2 ..... E_{n-1} except E_n;

and μ_1, μ_2 .... μ_n

Step 2. Use B727-200 as the most common aircraft in operation. Determine its equivalent single wheel load and the corresponding tire pressure, p, and radius of foot print area, a.

Step 3. Convert E-value to pavement surface deflection by

$$w_o = \frac{2pa}{E}(1-\mu^2)$$

Step 4. Determine subgrade E_n by iteration process when computed surface deflection by GELS is equal to w_o.

Step 5. Modify E_n for drainage condition.

Step 6. Reverse iteration process to determine surface deflection for modified E_n.

Step 7. Convert surface deflection to E-value.

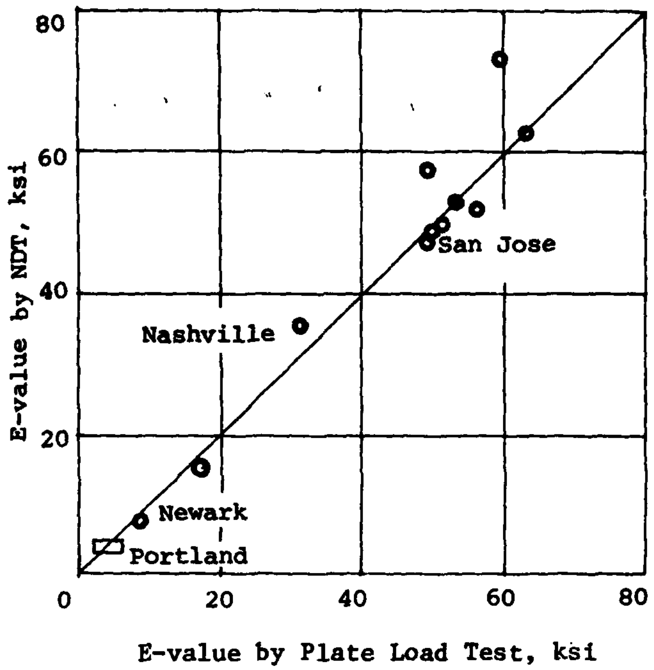
There are four E-values for every test point

1. E-value of pavement surface for drainage condition observed.
2. Subgrade E-value for drainage observed.
3. Subgrade E-value for modified drainage condition.
4. E-value of pavement surface for modified drainage condition.

Computer Output:

NDT Inventory File

Correlation of NDT with Plate Load Test.



FAA Soil test requirements	
Liquid Limit	30%
Plastic Limit	13
Finer than 200 sieve	70.4
FAA Classification	E-7
E-value of Subgrade by NDT	11,500 psi

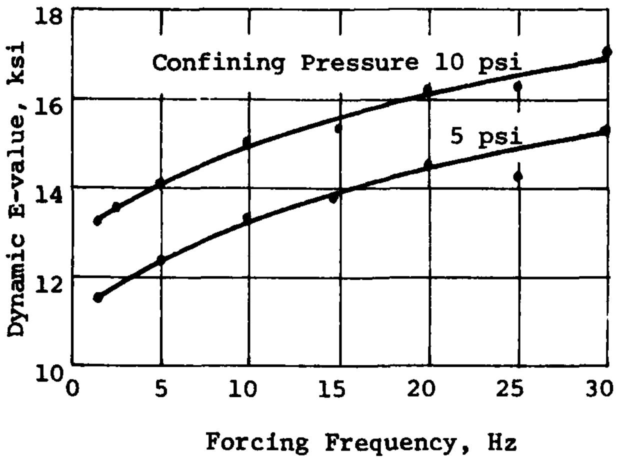
No Correlation

Conventional Soil Tests	
Triaxial Test	150-540 psi
Resilient Test @ 5 Hz, 3 second interval	1900-4300 psi
E-value of Subgrade by NDT	7000 psi

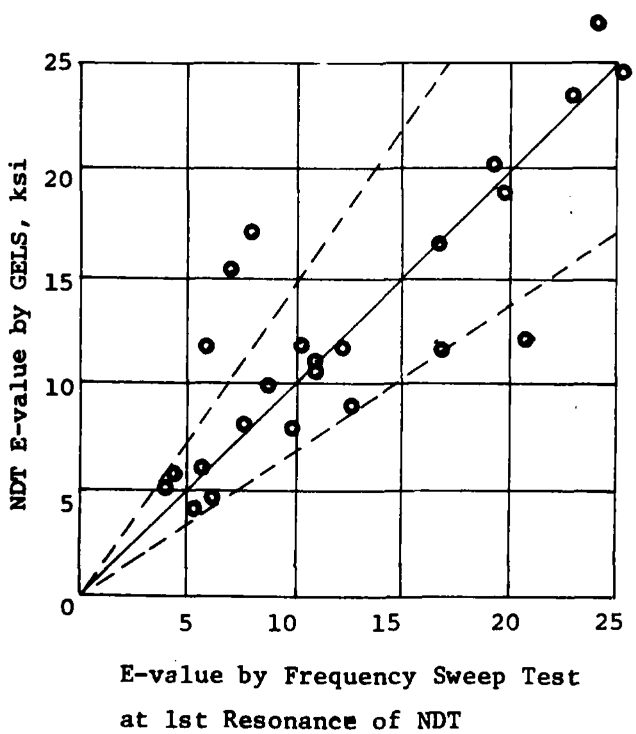
There is some correlation between NDT-E and resilient modulus.

Introducing New Soil Testing Procedure

1. Similar frequency sweep method is used for soil test (triaxial) at various confining pressure settings.
2. Low pressure and 1st NDT resonant frequency is used for E-value selection.

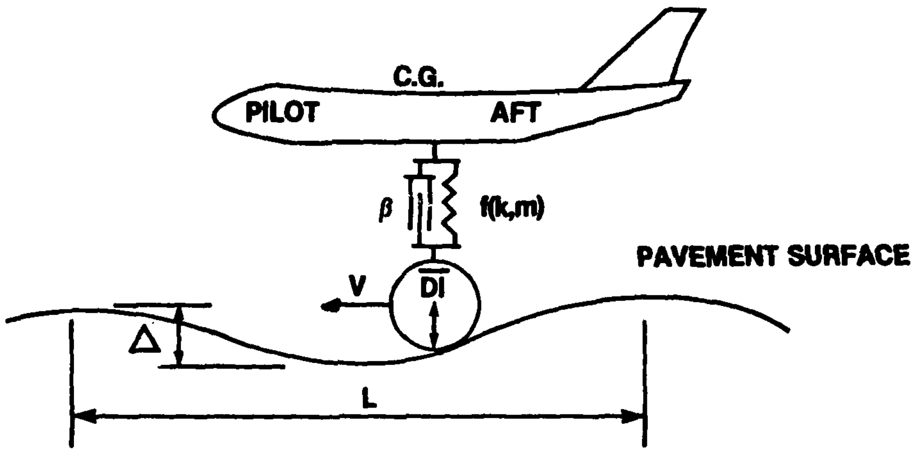


Correlation of NDT with Frequency Sweep Soil Test

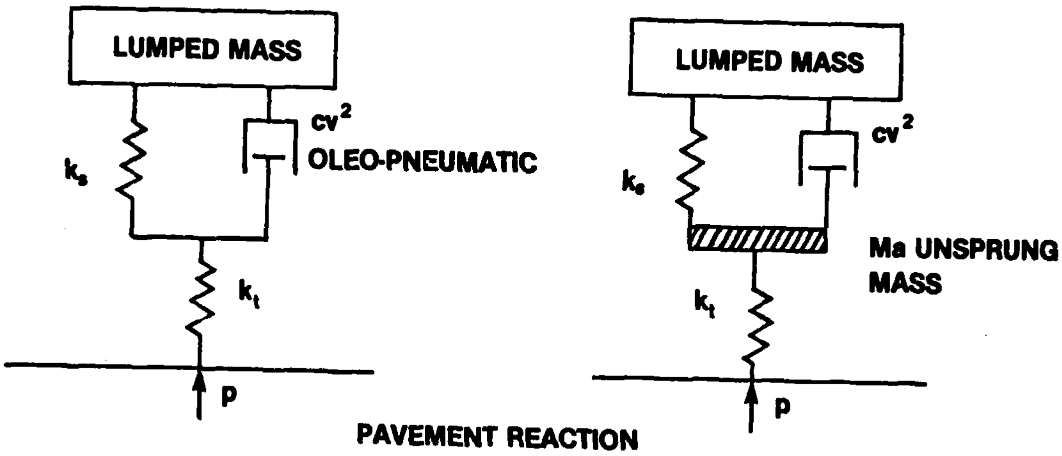


SESSION 2

AIRCRAFT-PAVEMENT INTERACTION



CHARACTERIZING SIMPLE PHYSICAL MODEL



LOW SPEED TAXIING **HIGH SPEED TAXIING**

First Level of Interaction

1. Aircraft is forcing function
2. Pavement is responding

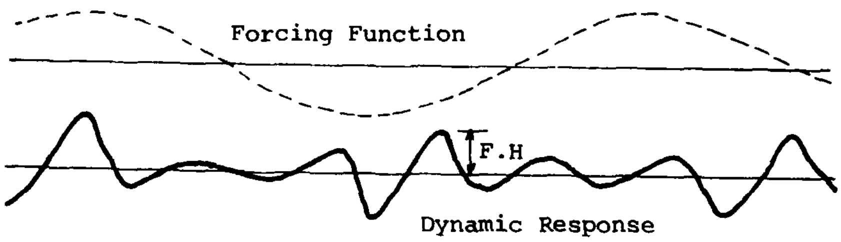
Transient Vibration

1. Forcing Function is a moving load.
2. No initial vibration and dumping

$$- z = \frac{M_v}{M_p} \cdot \frac{1}{(2\pi f)^2} \cdot \ddot{z} \sin 2\pi\omega t$$

Steady State of Vibration

1. Forcing function is a stationary F $\sin 2\pi\omega t$
2. Initial vibration is not significant.



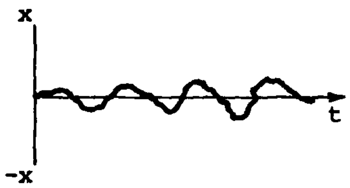
Second Level of Interaction

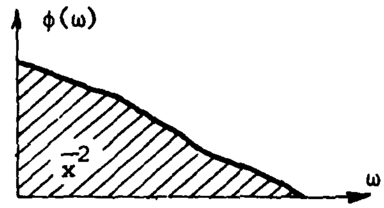
Random vibration of aircraft on rough surface

1. Rough surface is forcing function.
2. Moving aircraft is responding.

Characterizing Pavement Roughness

Roughness is a multi-frequency random input, and can be expressed by $\bar{x}^2 = \frac{1}{T}\int_o^T x^2.dt$





Introducing Concept of Power Spectral Density

$$\phi(\omega) = \lim_{\Delta\omega \to o} \frac{\Delta x^2}{\Delta\omega}$$

or $$\bar{x} = \int_o^\infty \phi(\omega).d\omega$$

Characterizing Aircraft Response

Simple frequency function $F = F_o \sin 2\pi\omega t$

$$\bar{F}^2 = \frac{1}{T}\int_o^T F_o^2 \sin^2 \pi\omega t.dt = F_o^2/2$$

Multi-frequency Response $\bar{F}^2 = \sum^n F_n^2/2$

Aircraft-Pavement Interaction

$$\bar{F}^2 = \sum^n \frac{F_o^2}{2} H_n^2 = \int_o^\infty \phi(\omega).H_\omega^2.d\omega$$

In a narrow frequency spectrum, i.e. $\phi(\omega)$ is a constant,

$$\bar{F}^2 \simeq \phi(\omega) \cdot \frac{\pi f}{4\beta}$$

In words: Mean square response of aircraft vibration is equal to the power spectral function $\phi(\omega)$ of pavement surface times the transfer function $\frac{\pi f}{4\beta}$ of aircraft.

Third Level of Interaction

1. Aircraft is forcing function again
2. Initial dynamic increment, $\overline{DI}$ due to rough riding
3. Pavement is response function and receive dynamic aircraft load as impact.

Dynamic Response of Pavement

$$- z = (1+\overline{DI}).\frac{F}{kg}.\bar{z}\ \sin 2\pi\omega t$$

Assumption: No initial vibration of pavement at the beginning of interaction.

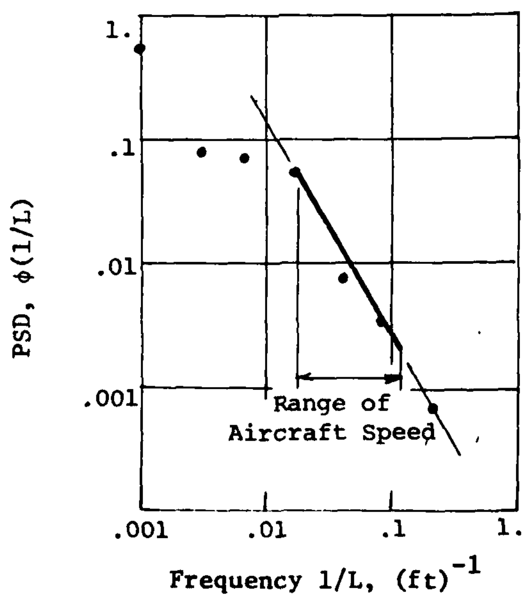
In general: Impact load on pavement is about 3 to 5% greater than the dynamic response of a riding aircraft.

Field Experiment

Profile Survey of RW 4R-22L, JFK

Power Spectral Density by Folding Frequency Method

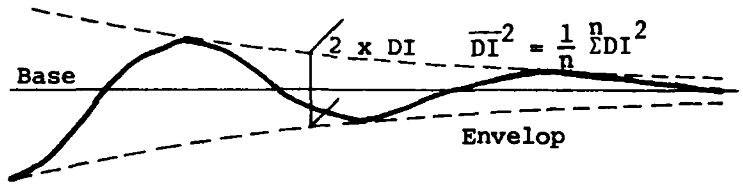
$$\bar{x}^2 = \Sigma\ \phi(\omega).d\omega \text{ in which } \omega = 1/L$$



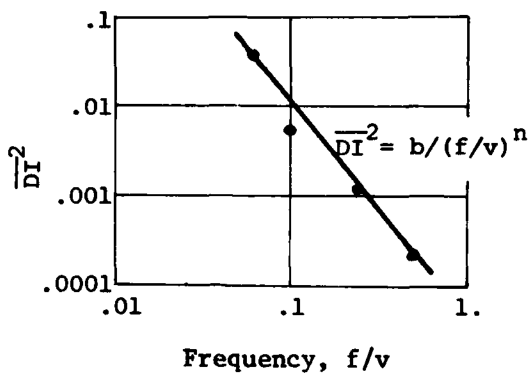
Field Measurement of Aircraft Response

1. Instrumented Aircraft FAA's CV880.
2. Vibration monitored at tire axle of MLG.
3. Constant aircraft speed at measurement.

Process of Field Data for one test speed.



Processed Data for all test speeds



Pavement-Aircraft Interaction

Max. vibration of aircraft occurs when significant wave length is equal to the crossing speed of aircraft per cycle of its natural frequency. $L = v/f$

$$\overline{DI}^2 = \phi(1/L).(b/c).(1/v)^{(m-n)}.f^m/f_o^n$$

f_o = Natural frequency of test aircraft.

Straightedge Method

$$\phi(1/L) = (\Delta^2/L)(v^2/f.f_o)/8$$

or $\Delta^2 = (8c/b)\ v^{(m-n)}.f_o^{(n+1)}.(\overline{DI}/v)^2.L/f^{(m-1)}$

$m \sim n \sim 2.0$

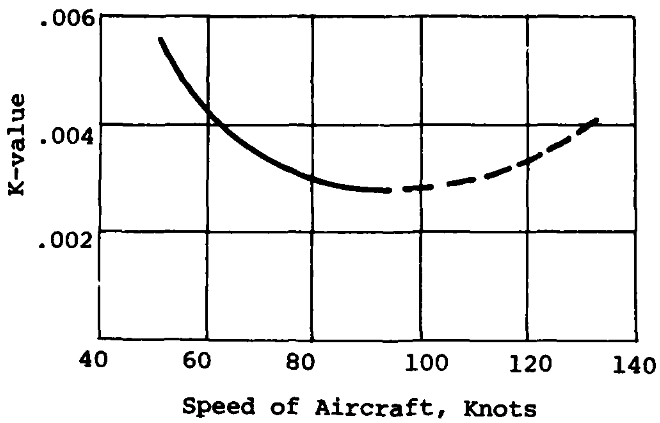
Houbolt, Ref. [7] (see p. 90), simplified the relation to

$\Delta = KL^{1/2}$

in which $K = C_o.(DI/v)/f^{1/2}$

Result of Aircraft Test - JFK

Straight Edge Method $\Delta = KL^{1/2}$

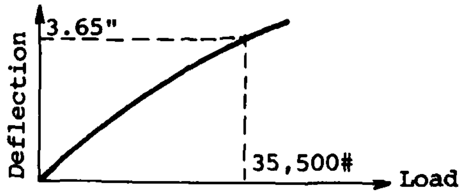


Significant Wave Length

Taxiway	30 - 60 kts	40 - 100 ft.
Runway	120 - 150 kts	140 - 200 ft.
Future Low Frequency Aircraft		250 - 300 ft.

Natural Frequency of Aircraft at Interface with Pavement.

Spring Constant of Tire = 35,500/3.65 = 9726 lbs./in



Max. Wheel Load = 43,000 lbs.

Mass = 43,000/386 = 111.4 $\text{lb-sec}^2/\text{in}$

$\omega = \sqrt{k/m} = \sqrt{9726/111.4} = 9.34$

$f = \omega/2\pi = 9.34/2\pi = 1.49$ Hz

Computer Default Value = 1.4 Hz

Spring constant is softer when the wheel load is less.

Limiting Elastic Deflection of Pavement Surface

Flow Chart:

Aircraft	Transfer Function	
$\overline{DI}, v, f, \beta$ →	TF1 → Δ, L	Long Deformation
	TF2 → DN, XX	Trans. Deformation
	TF3 → DO(N,DN)	Rate of Deformation
	TF4 → WZ, WO	Elastic Deformation
	Elastic Theory	→ Pavement Design

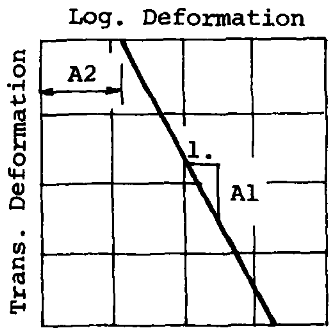
Transfer Function TF1

$$\Delta = KL^{1/2}$$

in which $K = C_o \cdot (\overline{DI}/v)/f^{1/2}$

$$C_o = T\ (f, \beta)$$

Transfer Function TF2



$$\log(DN/\sqrt{XX}) = A1 * (\log(\Delta N/\sqrt{L}) - \log A2)$$

A1, A2 = Coefficients of transfer function

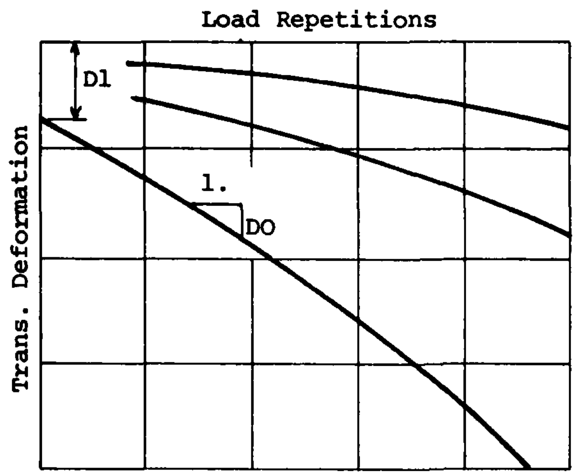
DN = Trans. deformation at N-th load repetition

AN = Long. deform. at N-th load repetition

XX = Width of deflection basin

= $8.6a + x_o$ @ 85% deflection.

Transfer Function TF3



DN = D1 + DO * log N

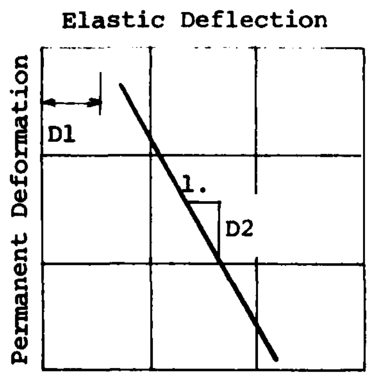
D1 = Experiment Data by Test

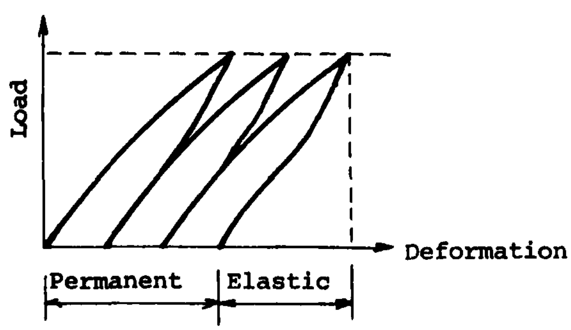
Given DN and N, Determine DO

or Given DN and DO, Determine N

DO = Rate of Trans. Deformation.

Transfer Function TF4

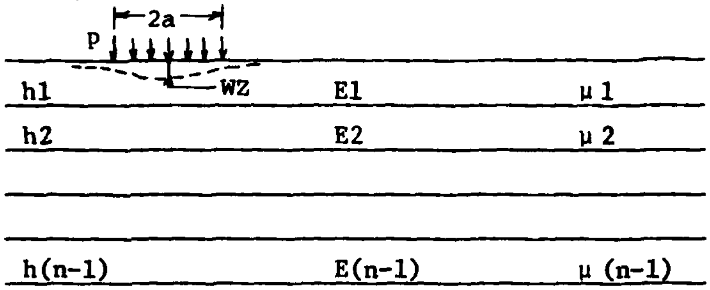




Elastic Theory for Pavement Design

General Equilibrium of Layered System

GELS



∞ $$E_s = \frac{2pa}{w_o}(1-\mu_n^2)$$ μn

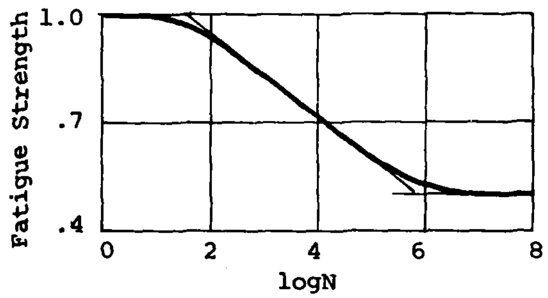
Given: a = Radius of tire footprint
p = Tire pressure
WZ = Limit elastic deflection
E_s = ESUB from NDT inventory file

Default or known Material Values:
All h, E & μ-values except one unknown to be determined by iteration of GELS.

Thickness Design: Concrete Slab
Lower Asphalt Layer
Lower Stabilized Base

LIMITING STRESS LEVEL

1. Fatigue Strength of Material



Fatigue Strength = $(1 - c \log N)\sigma_y$

2. Over-stress Factor $(1+s_o)$

Larger s_o-value for permissible maintenance, less traffic, and/or time-temp. dependent.

3. Quality variance of component material $(1-\nu)$

ν = variance of material strength.

σ_k = characteristic strength

σ_m = mean value of test results

$\sigma_s = \nu .\ \sigma_m$ = standard deviation of test

k = coefficient depending on performance reliability

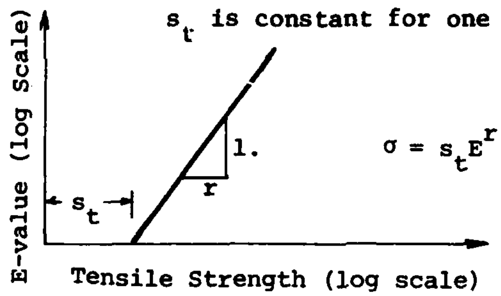
$\sigma_k = \sigma_m(1-k\nu)$

k-value	Reliability
1.0	.841
2.0	.977
3.0	.999

4. Convert E-value to Tensile Strength,

Default Value: $r = \frac{1}{2}$

s_t is constant for one type material.



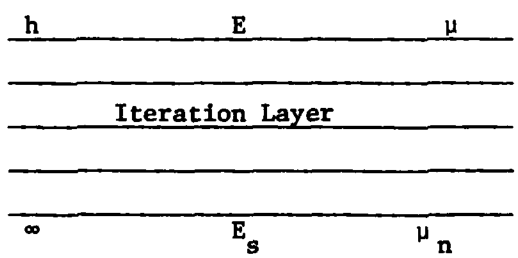
5. Dynamic Impact of Aircraft, $\overline{DI}$

   Allowable working stress = $s_t\sqrt{E}/(1+\overline{DI})$

6. Considering all factors, limiting work stress

   $\sigma_t = (1-c.\log N).(1+s_o).(1-\nu).s_t\sqrt{E}/(1+\overline{DI})$.

7. Pavement Thickness Design



Given all E, h and μ except one thickness

Determine: Thickness of iteration layer.

Condition: Layer stress computed by GELS is less than or equal to σ_t.

SESSION 3

FORECAST OF AVIATION DEMAND

An input developed by Airport Users, ATA, and Airport Operator of each individual airport.

ATA supplies information on the development of future transport.

An accurate forecast is still more of an art than a science.

Pavement evaluation and design depend less on the accuracy of a forecast than the projection of facility capacity. Nevertheless, the computer analysis will reflect three forecast conditions:

Half, Full and Double demand forecast

A reliable demand forecast can be deduced from the study of the following pertinent factors:

- Demand Forecast of Air Trade Area
- Scheduled Air Carriers
- Passenger Seat Capacity
- Fleet Mix and Flight Route
- Operational Weight of Aircraft
- G.A., Military and Cargo

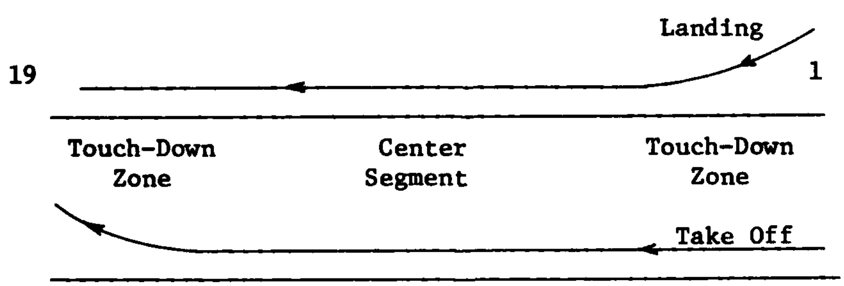
Computer Input in Average Daily Movement

ADM ATA	Forecast by ATA
ADM FAA	Forecast by FAA
ADM APO	by Airport Operator
ADM SUG	for Pavement Design

Utilization of PAF

Longitudinal Distribution:

Traffic on Runway

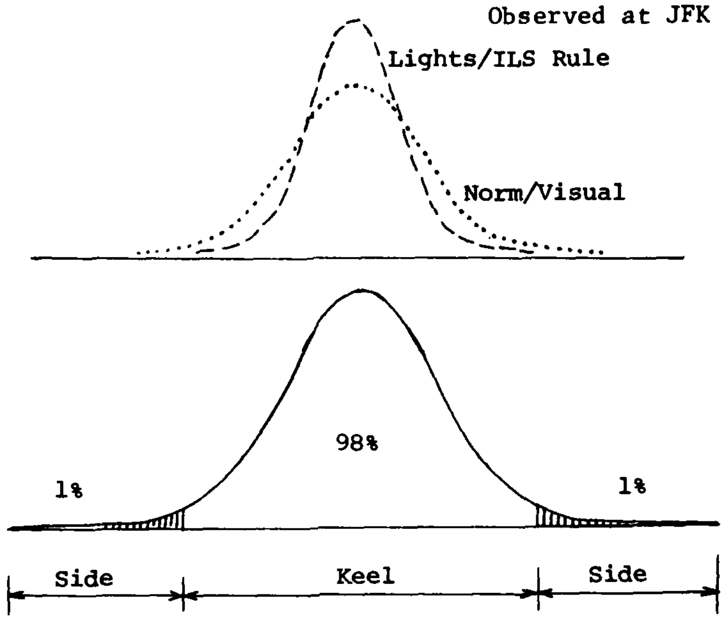


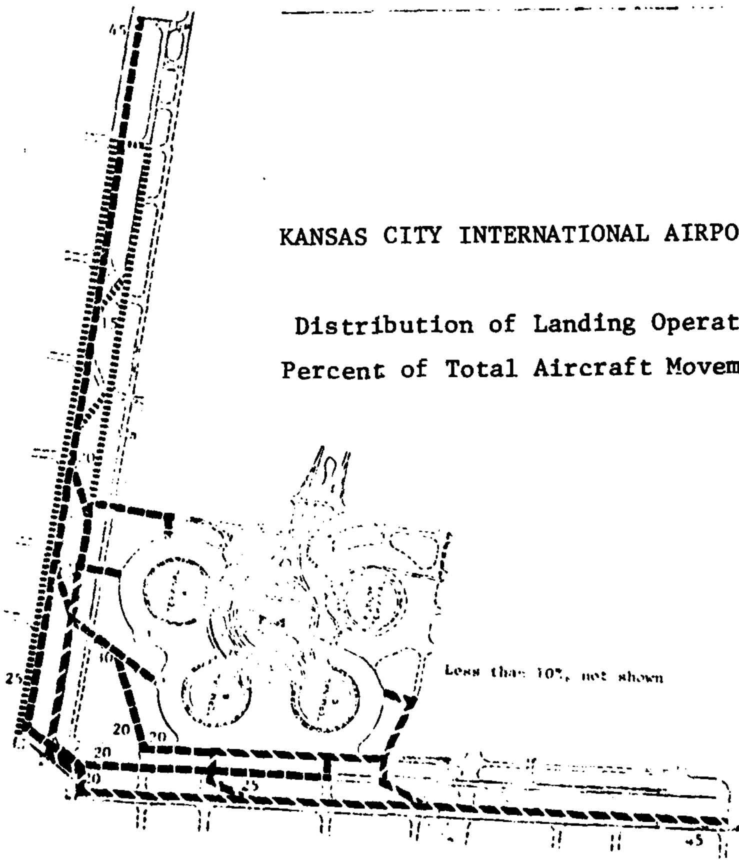
Load Distribution

R/W 1	-	TOW (1)	TOW (1)
	LRW (1)	LRW (1)	LRW (1)
	-	-	TDW (1)
RW 19	TOW (19)	TOW (19)	-
	LRW (19)	LRW (19)	LRW (19)
	TDW (19)	-	-

Transverse Distribution

Traffic on Runways & Taxiways





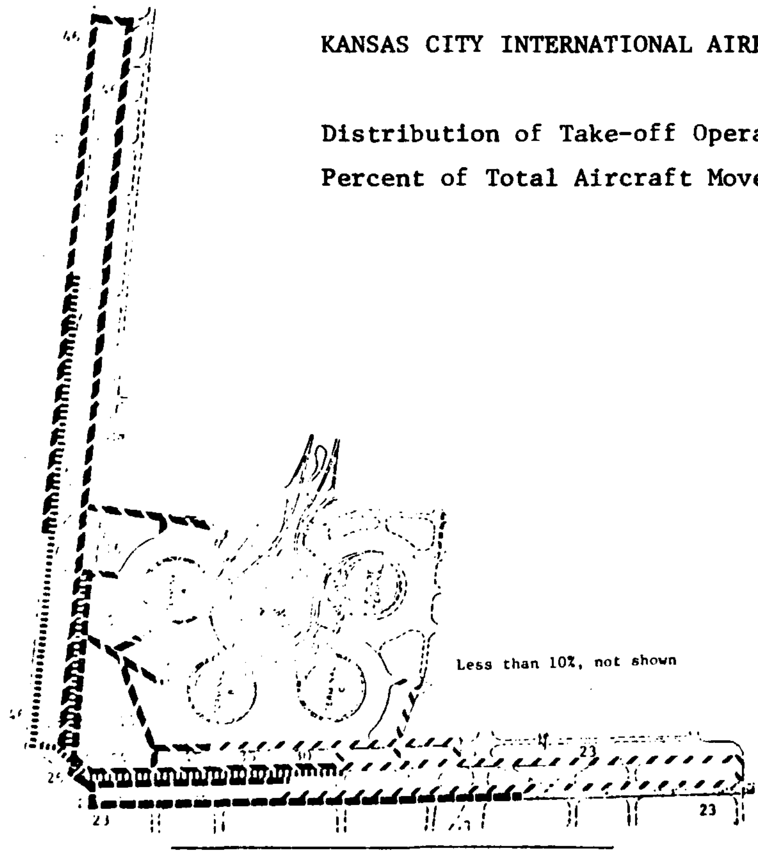
KANSAS CITY INTERNATIONAL AIRPORT

Distribution of Landing Operation
Percent of Total Aircraft Movement

KANSAS CITY INTERNATIONAL AIRPORT

Distribution of Take-off Operation

Percent of Total Aircraft Movement



Equivalent Single Type of Aircraft Movement

Inputs: Fleet of Average Daily Movement, ADM

Airport Traffic Distribution, ATD

Process: Converting a fleet of aircraft movement to an equivalent movement of a single type of aircraft according to its cumulative damage to pavement system.

Step

1. Tabulate Airport Traffic Movements for each facility during a given year of operation.
2. Introduce default pavement system, PFLPAV, for equivalency analysis of existing pavements.

3. Compute touch-down and landing roll weight from operational take-off weight

   LRW = OEW + (MLRW-OEW)*(TOW-OEW)/(MTOW-OEW)

   TDW = 1.5 * LRW for sinking velocity of 4 fps.

4. Compute the following data for three operation weights of every aircraft.

   Radius of tire foot-print area;

   Transverse probability distribution, APX;

   Longitudinal probability distribution of touch-down weight, APY.

5. Compute surface deflection and component stress by GELS for each type of PFLPAV under three aircraft weights for every type of aircraft.

---

6. Compute equivalent aircraft operation

   i - Type of aircraft to be equilized (12)

   j = Operational weight of that aircraft (3)

   m = Aircraft selected as design standard

   n = Operational weight as design standard.

   Equivalent Aircraft Operation = N(i,j)/N(m,n).

   Limiting Stress Criteria:

   $$\log N(i,j) = (\sigma_y - \sigma_t(i,j))/c.\sigma_y$$

   $$\sigma_y = (1+s_o)(1-\nu)(s_t\sqrt{E})/(1+\overline{DI})$$

   $$\log ANS(i,j) = \log\frac{N(i,j)}{N(m,n)} \cdot \frac{\log N(ATM)}{\log N(i,j)}$$

   $$\log N(ATM) = \log(APX(m,n)*APY(m,n)*ATM(m,n))$$

   Limiting Deflection Criteria:

   $$\log N(i,j) = (D_n-D_1)(d_1)^{d2}W_o(i,j)^{(d2-1)}W_z(i,j)^{-d2}$$

   $$\log AND(i,j) = \log\frac{N(i,j)}{N(m.n)} \cdot \frac{\log N(ATM)}{\log N(i,j)}$$

7. Equivalent Single Type of Aircraft Operation

Stress Criteria:

$$\sum^{i}\sum^{j} ANS(i,j) = AANS$$

i = 12 or types of aircraft

j = 3 operational weights

Deflection Criteria:

$$\sum^{i}\sum^{j} AND(i,j) = AAND$$

Single type of aircraft operation is for

m aircraft in grid of inventory file (Normally, it is B727-200 but can be any aircraft in the file);

n operational weight (Normally it is take-off weight, but can be any operational weight, such as landing roll or touch down weight).

Capacity of Existing Pavements

Step

1. Assign the type of aircraft that is to be the standard for pavement design. B727-200 is, in general, the governing aircraft for all pavements with respect to stress and deflection criteria, except B747 for deflection criteria or DC-10 for stress criteria if the operation of such wide-bodied jets is predominant.
2. Compute, by GELS, the surface deflection and component stress of existing pavements, PFLPAV, for E-subgrade tabulated in NDT inventory file.

3. Anticipated Capacity - Load Repetition

Deflection Criteria

$$
\begin{tikzcd}
\text{Aircraft vibration} \arrow[r] & TF1 \arrow[d] & \\
& TF2 \arrow[r] & DN \arrow[dddl] \\
\text{Existing pavement} \arrow[r] & GELS \arrow[d] & \\
& TF4 \arrow[r] & DO \arrow[dl] \\
& TF3 \arrow[r] & ANDA
\end{tikzcd}
$$

ANDA = life capacity of existing pavement with respect to deflection criteria

Stress Criteria

$$\log (ANSA) = (\sigma_y - \sigma_t)/c.\sigma_y$$

ANSA = life capacity of existing pavement with respect to stress criteria

σ_t = computed stress from GELS

$\sigma_y = (1+s_o)(1-\nu)(s_t\sqrt{E})/(1+\overline{DI})$

Inventory of Present Functional Life

1. Governed by pavement surface deflection and aircraft vibration at pavement-tire interface, over and above the roughness of existing riding condition.

$$DEF/DI = \frac{\text{Present Capacity}}{\text{Annual Traffic}} = \frac{ANDA}{AAND}$$

2. Governed by stress level in the most critical pavement component.

$$STR/MT = \frac{\text{Present Capacity}}{\text{Annual Traffic}} = \frac{ANSA}{AANS}$$

A reflection of maintenance needs.

3. Interpretation of PFL

Function of Pavement Surface

Maintenance Needs -- Structural Integrity

Maintenance Needs -- Subsurface Drainage

SESSION 4

PAVEMENT DESIGN AND COST-BENEFIT STUDY

Design Thickness and Composition

1. Establish Default Input Files

Facility Type	RW, TW, HP
Bandwidth	Lights, Norm

DI, VEL, Keel-side Identification

Layer Components and E-values

Material & Transfer Function Coefficients

Standard Aircraft for Design

Aircraft File

Default System of Existing Pavements, PFLPAV

Default System for Pavement Design, PAM

Layer Governed by Stress Limit, STR/MT

GELS Grid System for Thickness Design

2. Job Inputs

   NDT Inventory File

   Operational Aircraft Weight

   Average Daily Movement

   Airport Traffic Distribution

   Design Command

      Facility

      Service Year

      Bandwidth

      Forecast

3. Computer Operation:

   To determine the number of load repetitions AAND and AANS by same procedure used for PFL. Default system for pavement design is PAM which is very similar to the composition of final pavement design.

---

4. Compute Deflection Limit:

   $$\text{Aircraft Vibration} \longrightarrow \boxed{\begin{array}{c}\text{TF1}\\ \text{TF2}\\ \text{TF3}\\ \text{TF4}\end{array}} \longrightarrow \text{WZ, WO}$$

   Listed under Limit DEF/WZ;

5. Compute Stress Limit:

   $$\sigma_t = (1-c.\log N)(1+s_o)(1-\nu)(s_t\sqrt{E})/(1+\overline{DI})$$

   Listed under limit stress for the governing component layer;

6. Determine pavement thickness by iteration process, i.e., the computed stress or deflection by GELS, is less than, but almost equal to the stress and deflection limit derived under Step 4 and Step 5. The designed layer thickness is governed by limiting deflection or stress which ever requires greater thickness.

7. Type of New Pavement

Pavement	Code	Layer	Thickness
1	LCF	ASTOP	3"
		LCFA	6"
		LCFB	6"
		LCFC	***
		SUB	+++
2	AC	ASTOP	2"
		ASBS	***
		AGBS	6"
		SUB	+++
3	CC	PCC	**
		CTB	6"
		SSBS	8"
		SUB	+++
7	CCL	PCC	10"
		RLC	***
		SSBS	6"
		SUB	+++

8. Asphalt Overlay on Existing Pavement

8	AC/PAV	ASTOP	1"
		ASBS	***
		PFLPAV	+++

9. Concrete & LCF Overlay on Existing Pavement

4	LC/PAV	ASTOP	3"
		LCFA	***
		PAV	+++
6	CC/PAV	PCCR	***
		ASTOP	1"
		PAV	+++

+++ test data from NDT Inventory File

*** denotes layer thickness by GELS iteration governed by limiting deflection or stress which ever requires greater thickness. The control condition is printed out as either governed by "DEF/DI" or "STR/MT".

10. For an average 2-runway airport, total number of thickness computations are about 200,000 units for 3,000 sets of pavement design. Actual print-out of thickness design is about 10,000 units.

COST BENEFIT ANALYSIS

1. Default System for Cost Analysis

Regional Cost Values for

ASO	Atlanta
ANE	Boston
AGL	Chicago
ASW	Dallas
ARM	Denver
ACE	Kansas City
AWE	Los Angeles
AEA	New York
ANW	Seattle

Component Cost for PCBT, FLAGT, COAGT
ASCLT, HLBT, POZBT
SFST, IWFAT, RSWLB
LBBM, CLHR, SLEHR

Financial Cost Elements:

AIRB	.08
ARCD	.10
ASCCC	.09
ASCMC	.02
NBL	30 yr.
NSLP	20 yr.

2. Job input if available

---

3. Compute Unit Component Price

Job input cost item * Default Element Values

= Unit Price of Component Layer

Dollar per inch per square yard.

4. Initial Construction Cost, ICC, is equal to the summation of layer cost which is the product of unit price times layer thickness from composition design.

5. Annual Maintenance Cost, AMC

AMC = ICC * COVAR (ULSTR-WOSTR)/(ULSTR-ACSTR)

COVAR = Variance of component strength

ULSTR = Ultimate strength of component

WOSTR = Allowable working stress

ACSTR = Actual stress by GELS.

6. Convert ICC to Present Cash Value, PCV
   Because the rate of cash discount is usually 2% higher than the annual interest on airport bonds, present cash value of initial construction cost, PCVICC, is always less than the ICC.
7. Convert AMC to present cash value PCVAMC by normal mortgage fund method.
8. Cost analysis is listed by
   PCV = PCVICC + PCVAMC

   for the variables:

   facility, station, location, DI, VEL, navigation, traffic forecast, design year, E-sub, PFLPAV, pavement composition and subgrade drainage.

---

9. Weighted Average of PCV for each Facility
   PCV = Σ PCVKEEL(I) * L(I) * WK/(L * WD)
   +Σ PCVSIDE(I) * L(I) * (WD-WK)/(L * WD)

L	=	total facility length
L(I)	=	segment length
WD	=	width of facility pavement
WK	=	width of keel section
PCVKEEL	=	PCV of keel section
PCVSIDE	=	PCV of side pavement

10. Cost Benefit is listed by
    facility, design year, navigation, traffic forecast, normal drainage for 10 pavement systems.
11. For different drainage condition and traffic volume, another design command should be filed for appropriate computer process.

APPENDIX 2 NDT INVENTORY FILE AND PRESENT FUNCTIONAL LIFE

CONTENTS

BURLINGTON INTERNATIONAL AIRPORT - FAA NEW ENGLAND REGION

NDT INVENTORY FILE

FACILITY	CODE	STA-FROM	STA-TO	DRAINAGE AT TEST	EPAV NORM	EPAV WET	ESUB NORM	ESUB WET	PFLPAV
1	RW 15-33	0.0	3.00	NORM	179545.	126113.	34283.	20570.	13 CC7
		3.00	69.00	NORM	34885.	25165.	14158.	8495.	2 AC2
		69.00	76.50	NORM	27745.	19696.	13980.	8388.	1 AC1
		76.50	80.00	NORM	165589.	117538.	30628.	18376.	13 CC7
2	RW 1-19	16.00	52.00	NORM	32267.	22872.	17732.	10639.	1 AC1
3	TW A	16.00	51.00	NORM	29191.	20480.	15015.	9009.	1 AC1
4	GATE/APRN	26.00	35.00	NORM	21726.	15641.	9903.	5942.	1 AC1
5	XTWS TO A	0.0	0.0	NORM	22234.	15992.	10239.	6143.	1 AC1
6	TW B	0.0	9.00	NORM	32320.	22928.	17788.	10673.	1 AC1
7	TW C	0.0	22.00	NORM	34350.	25115.	19810.	11886.	1 AC1
8	APRON GA	6.00	15.00	NORM	52994.	37313.	7899.	4739.	14 OC1
9	TW D	0.0	25.00	NORM	31625.	22208.	17037.	10222.	1 AC1
10	TW E	1.00	6.00	NORM	26376.	18699.	12896.	7738.	1 AC1
11	TW F	1.00	49.00	NORM	36029.	26245.	21310.	12786.	1 AC1
12	APRN VANG	48.00	63.00	NORM	24670.	17331.	11656.	6994.	1 AC1
13	RW1-19EXT	0.0	16.00	NORM	10667.	6400.	10667.	6400.	0 SUB
14	TW NEW	0.0	37.00	NORM	10395.	6237.	10395.	6237.	0 SUB
15	XTW-GA NU	0.0	10.00	NORM	10381.	6229.	10381.	6229.	0 SUB
16	TW - RW19	0.0	18.00	NORM	10327.	6196.	10327.	6196.	0 SUB

BURLINGTON INTERNATIONAL AIRPORT - FAA NEW ENGLAND REGION

SUMMARY OF PRESENT FUNCTIONAL LIFE

AS MEASURED BY PROGRESSIVE DETERIORATION OF EXISTING
PAVEMENT SURFACE DUE TO ANTICIPATED AIRCRAFT MOVEMENTS

DI =0.12G SMOOTH PAVEMENT SURFACE
DI =0.18G OPERATIONAL SURFACE
DI =0.25G UPPER LIMIT OF ROUGHNESS TOLERANCE

						PFL IN YEARS (1977 TRAFFIC)										
						GOVERNED BY DEF/DI							GOVERNED BY STR/HT			
FACILITY	STATION FROM-TO	VEL	NDT/3 ESUB NORM	NDT/3 ESUB WET	PFLPAV	DI .12G NORM	.18G NORM	.25G NORM	.12G WET	.18G WET	.25G WET	IMPACT	.18G NORM	.30G NORM	.18G WET	.30G WET
RW 15-33	0.- 3.	145.	34283.	20570.	13 CC7	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 15-33	3.- 30.	145.	14158.	8495.	2 AC2	2.16	>5.00	>5.00	1.19	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 15-33	30.- 53.	145.	14158.	8495.	2 AC2	2.50	>5.00	>5.00	1.39	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 15-33	53.- 69.	145.	14158.	8495.	2 AC2	1.51	>5.00	>5.00	0.84	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 15-33	69.- 77.	145.	13980.	8388.	1 AC1	0.31	>5.00	>5.00	0.19	3.78	>5.00		>5.00	4.03	0.00	0.00
RW 15-33	77.- 78.	145.	30628.	18376.	13 CC7	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 1-19	16.- 52.	145.	17732.	10639.	1 AC1	3.92	>5.00	>5.00	2.39	>5.00	>5.00		>5.00	>5.00	0.06	0.00
TW A	16.- 51.	50.	15015.	9009.	1 AC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	0.00	0.00
GATE/APRN	26.- 35.	50.	9903.	5942.	1 AC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.00	0.00	0.00	0.00
XTWS TO A	0.- 0.	50.	10239.	6143.	1 AC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.02	0.00	0.00	0.00
TW B	0.- 9.	50.	17788.	10673.	1 AC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	0.05	0.00
TW C	0.- 22.	50.	19810.	11886.	1 AC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	0.89	0.10
APRON GA	6.- 15.	50.	7899.	4739.	14 CC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.04	0.00	0.00	0.00
TW D	0.- 25.	50.	17037.	10222.	1 AC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	0.02	0.00
TW E	1.- 6.	50.	12896.	7738.	1 AC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	2.33	0.00	0.00
TW F	1.- 49.	50.	21310.	12786.	1 AC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	3.47	0.47
APRN VANG	48.- 63.	50.	11656.	6994.	1 AC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.72	0.08	0.00	0.00

STAPLETON INTERNATIONAL AIRPORT - FAA ROCKY MOUNTAIN REGION

NDT INVENTORY FILE

FACILITY	CODE	STA-FROM	STA-TO	DRAINAGE AT TEST	EPAV NORM	EPAV WET	ESUB NORM	ESUB WET	PELPAV
1	RW17L-35R	120.00	150.50	NORM	125396.	93255.	20399.	12239.	13 CC7
		150.50	200.50	NORM	176434.	124215.	33518.	20111.	13 CC7
		200.50	236.50	NORM	150730.	107020.	25991.	15595.	13 CC7
2	RW17R-35L	60.00	82.20	NORM	189795.	158187.	83590.	50154.	17 OC4
		82.20	83.10	NORM	119665.	92237.	26074.	15645.	17 OC4
		83.10	107.20	NORM	141403.	110053.	37567.	22540.	17 OC4
		107.20	108.70	NORM	73543.	54169.	10762.	6457.	~~17 OC4~~ I-70
		108.70	151.00	NORM	160905.	121251.	51019.	30612.	9 CC3
		151.00	175.00	NORM	144249.	107437.	40987.	24592.	9 CC3
3	TW Z	44.00	82.20	NORM	121943.	87568.	22564.	13538.	11 CC5
		82.20	83.10	NORM	108531.	77463.	18980.	11388.	11 CC5
		83.10	107.20	NORM	155871.	111102.	32889.	19734.	11 CC5
		107.20	108.70	NORM	138973.	100469.	27275.	16365.	11 CC5
		108.70	236.00	NORM	135504.	97134.	25949.	15569.	11 CC5
4	XTW Z1-Z9	1.00	4.10	NORM	146418.	105191.	29908.	17945.	11 CC5
		4.10	9.00	NORM	124930.	89371.	23257.	13954.	11 CC5
		9.00	14.00	NORM	129581.	92151.	24273.	14564.	11 CC5
5	TW L	59.00	91.00	NORM	139063.	101766.	38365.	23019.	9 CC3
		91.00	126.00	NORM	171824.	133003.	58405.	35043.	9 CC3
		126.00	176.00	NORM	154820.	114945.	46452.	27871.	9 CC3
6	XTW L1-L9	1.00	2.10	NORM	122591.	88932.	31158.	18695.	9 CC3
		2.10	4.10	NORM	129213.	93061.	33690.	20214.	9 CC3
		4.10	5.10	NORM	158051.	118270.	48921.	29352.	9 CC3
7	RW 8R-26L	1.00	99.00	NORM	45528.	32785.	16158.	9695.	3 AC3
8	RW 8L-26R	81.00	110.00	NORM	67241.	46754.	11820.	7092.	9 CC3
		110.00	145.50	NORM	94098.	76715.	57498.	34499.	4 AC4
		145.50	159.00	NORM	125123.	112264.	125000.	75000.	5 AC5
9	TW C	0.0	12.00	NORM	71404.	54624.	30261.	18157.	4 AC4
		12.00	101.00	NORM	68590.	47662.	12127.	7276.	9 CC3
10	XTW C1-C9	1.00	1.50	NORM	42507.	23884.	6127.	3676.	9 CC3
		1.50	2.10	NORM	67764.	48990.	11799.	7080.	14 OC1
		2.10	3.10	NORM	64487.	45241.	11282.	6769.	9 CC3
		3.10	4.10	NORM	119557.	101011.	93090.	55854.	5 AC5
		4.10	5.10	NORM	62867.	48257.	18367.	11020.	5 AC5
		5.10	8.10	NORM	143503.	112264.	125000.	75000.	5 AC5
		8.10	12.00	NORM	77190.	54305.	14695.	8817.	9 CC3
11	TW D	5.00	56.00	NORM	102042.	72999.	18822.	11293.	10 CC4
12	XTW D1-D5	1.00	5.00	NORM	85414.	67747.	73947.	44303.	2 AC2
		5.00	8.00	NORM	115721.	96686.	125000.	75000.	3 AC3
13	APRON A	0.0	0.0	NORM	35660.	24831.	4380.	2628.	14 OC1
14	APRON B	0.0	0.0	NORM	56320.	39429.	9375.	5625.	9 CC3
15	APRON C	0.0	0.0	NORM	61462.	43548.	10635.	6381.	9 CC3
16	APRON D	0.0	0.0	NORM	59358.	42350.	10146.	6087.	9 CC3

NAI C. YANG, ENGINEERING CONSULTANT

STAPLETON INTERNATIONAL AIRPORT - FAA ROCKY MOUNTAIN REGION

SUMMARY OF PRESENT FUNCTIONAL LIFE

AS MEASURED BY PROGRESSIVE DETERIORATION OF EXISTING
PAVEMENT SURFACE DUE TO ANTICIPATED AIRCRAFT MOVEMENTS

DI =0.12G SMOOTH PAVEMENT SURFACE
DI =0.18G OPERATIONAL SURFACE
DI =0.25G UPPER LIMIT OF ROUGHNESS TOLERANCE

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						PFL IN YEARS (1977 TRAFFIC)									
						GOVERNED BY DEF/DI						GOVERNED BY STR/MT			
FACILITY	STATION FROM-TO	VEL	NDT/3 ESUB NORM	NDT/3 ESUB WET	PFLPAV	DI .12G NORM	.18G NORM	.25G NORM	.12G WET	.18G WET	.25G WET	IMPACT .18G NORM	.30G NORM	.18G WET	.30G WET
RW17L-35R	120.-151.	145.	20399.	12239.	13 CC7	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
RW17L-35R	151.-201.	145.	33518.	20111.	13 CC7	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
RW17L-35R	201.-237.	145.	25991.	15595.	13 CC7	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
RW17R-35L	60.- 82.	145.	83590.	50154.	17 DC4	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
RW17R-35L	82.- 83.	145.	26074.	15645.	17 DC4	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	1.02	0.64	0.09
RW17R-35L	83.-107.	145.	37567.	22540.	17 DC4	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	4.55	2.76	0.46
RW17R-35L	107.-109.	145.	10762.	6457.	~~17 DC4~~ I-70	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	0.09	0.01	0.01	0.00
RW17R-35L	109.-151.	145.	51019.	30612.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	2.56
RW17R-35L	151.-175.	145.	40987.	24592.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	2.46
TW Z	44.- 82.	50.	22564.	13538.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW Z	82.- 83.	50.	18980.	11388.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW Z	83.-107.	50.	32899.	19734.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW Z	107.-109.	50.	27275.	16365.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW Z	109.-123.	50.	25949.	15569.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW Z	123.-236.	50.	25949.	15569.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
XTW Z1-Z9	1.- 4.	50.	29908.	17945.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
XTW Z1-Z9	4.- 9.	50.	23257.	13954.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
XTW Z1-Z9	9.- 14.	50.	24273.	14564.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW L	59.- 91.	50.	38365.	23019.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW L	91.-126.	50.	58405.	35043.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW L	126.-176.	50.	46452.	27871.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
XTW L1-L9	1.- 2.	50.	31158.	18695.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	2.34
XTW L1-L9	2.- 4.	50.	33690.	20214.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
XTW L1-L9	4.- 5.	50.	48921.	29352.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00

STAPLETON INTERNATIONAL AIRPORT - FAA ROCKY MOUNTAIN REGION

SUMMARY OF PRESENT FUNCTIONAL LIFE

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PAVEMENT SURFACE DUE TO ANTICIPATED AIRCRAFT MOVEMENTS

DI =0.12G SMOOTH PAVEMENT SURFACE
DI =0.18G OPERATIONAL SURFACE
DI =0.25G UPPER LIMIT OF ROUGHNESS TOLERANCE

						PFL IN YEARS (1977 TRAFFIC)										
						GOVERNED BY DEF/DI							GOVERNED BY STR/MT			
FACILITY	STATION FROM-TO	VEL	NDT/3 ESUB NORM	NDT/3 ESUB WET	PFLPAV	DI .12G NORM	.18G NORM	.25G NORM	.12G WET	.18G WET	.25G WET	IMPACT	.18G NORM	.30G NORM	.18G WET	.30G WET
RW 8R-26L	1.- 31.	145.	16158.	9695.	3 AC3	0.03	>5.00	>5.00	0.01	>5.00	>5.00		>5.00	>5.00	>5.00	2.49
RW 8R-26L	31.- 69.	145.	16158.	9695.	3 AC3	0.02	>5.00	>5.00	0.01	>5.00	>5.00		>5.00	>5.00	>5.00	1.72
RW 8R-26L	69.- 99.	145.	16158.	9695.	3 AC3	0.07	>5.00	>5.00	0.03	>5.00	>5.00		>5.00	>5.00	>5.00	4.38
RW 8L-26R	81.-110.	145.	11823.	7092.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		1.67	0.22	0.17	0.02
RW 8L-26R	110.-130.	145.	57498.	34499.	4 AC4	0.28	>5.00	>5.00	0.67	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 8L-26R	130.-146.	145.	57498.	34499.	4 AC4	0.57	>5.00	>5.00	1.35	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 8L-26R	146.-159.	145.	125000.	75000.	5 AC5	0.13	>5.00	>5.00	1.18	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
TW C	0.- 12.	50.	30261.	18157.	4 AC4	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
TW C	12.- 30.	50.	12127.	7276.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.70	0.10	0.07	0.01
TW C	30.-101.	50.	12127.	7276.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	1.26	0.92	0.10
XTW C1-C9	1.- 2.	50.	6127.	3676.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.33	0.03	0.02	0.00
XTW C1-C9	2.- 2.	50.	11799.	7080.	14 CC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.00	0.00	0.00	0.00
XTW C1-C9	2.- 3.	50.	11282.	6769.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		1.05	0.14	0.11	0.01
XTW C1-C9	3.- 4.	50.	93090.	55854.	5 AC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
XTW C1-C9	4.- 5.	50.	18367.	11020.	5 AC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
XTW C1-C9	5.- 8.	50.	125000.	75000.	5 AC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
XTW C1-C9	8.- 12.	50.	14695.	8817.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	4.44	3.29	0.40
TW D	5.- 56.	50.	18822.	11293.	10 CC4	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
XTW D1-D5	1.- 2.	50.	73847.	44308.	2 AC2	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
XTW D1-D5	2.- 5.	50.	73847.	44308.	2 AC2	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
XTW D1-D5	5.- 8.	50.	125000.	75000.	3 AC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
APRON A	0.- 0.	50.	4380.	2628.	14 CC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.00	0.00	0.00	0.00
APRON B	0.- 0.	50.	9375.	5625.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.11	0.01	0.01	0.00
APRON C	0.- 0.	50.	10635.	6381.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.37	0.05	0.04	0.00
APRON D	0.- 0.	50.	10145.	6087.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.15	0.02	0.02	0.00

KANSAS CITY INTERNATIONAL AIRPORT - FAA CENTRAL REGION

NDT INVENTORY FILE

FACILITY	CODE	STA-FROM	STA-TO	DRAINAGE AT TEST	EPAV NORM	EPAV WET	ESUB NORM	ESUB WET	PFLPAV
1	RW 1L-19R	0.0	8.00	NORM	100078.	73527.	14645.	8787.	18 DC5
		8.00	50.00	NORM	83125.	60788.	10799.	6479.	18 DC5
		50.00	108.00	NORM	96256.	71190.	13691.	8215.	18 DC5
2	TW A	0.0	31.00	NORM	86753.	60457.	14445.	8667.	10 CC4
		31.00	90.00	NORM	70887.	49471.	10916.	6550.	10 CC4
		90.00	108.00	NORM	101383.	72259.	18606.	11164.	10 CC4
3	RW 9L-27R	0.0	6.00	NORM	94480.	69484.	20705.	12423.	9 CC3
		6.00	89.00	NORM	64813.	45421.	11348.	6809.	9 CC3
		89.00	95.00	NORM	82286.	57088.	15963.	9578.	9 CC3
4	TW C	0.0	26.00	NORM	77789.	54636.	14852.	8911.	9 CC3
		26.00	40.50	WET	52187.	35296.	8183.	4910.	9 CC3
		40.50	68.00	NORM	59767.	42584.	10243.	6146.	9 CC3
		68.00	88.00	NORM	75822.	53544.	14325.	8595.	9 CC3
		88.00	95.00	NORM	100842.	73420.	22739.	13643.	9 CC3
5	TW D	39.00	55.00	NORM	63985.	44962.	11178.	6707.	9 CC3
6	TW B	17.00	38.00	NORM	86051.	60995.	17548.	10529.	9 CC3
7	TM A	4.00	72.00	NORM	71167.	50321.	12961.	7777.	9 CC3
8	TM B	7.00	82.00	NORM	76741.	54056.	14575.	8745.	9 CC3
9	TM C	8.00	80.00	NORM	88163.	63312.	18396.	11038.	9 CC3
10	XTW A1-A9	1.00	9.00	NORM	77571.	54516.	14795.	8877.	9 CC3
11	XTW STUB	0.0	0.0	NORM	101356.	73735.	22892.	13735.	9 CC3
12	XTW C8-C1	1.00	8.00	NORM	71545.	50719.	13079.	7847.	9 CC3
13	XTW B3-B9	3.00	9.00	WET	55913.	39009.	9266.	5560.	9 CC3
14	XTW D7-D3	3.00	7.00	NORM	81229.	56517.	15713.	9428.	9 CC3
15	XTW F0-F1	0.0	1.00	NORM	88556.	63750.	18549.	11130.	9 CC3
16	XTW G1-G2	1.00	2.00	NORM	78622.	55095.	15068.	9041.	9 CC3

KANSAS CITY INTERNATIONAL AIRPORT - FAA CENTRAL REGION

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DI =0.12G SMOOTH PAVEMENT SURFACE
DI =0.18G OPERATIONAL SURFACE
DI =0.25G UPPER LIMIT OF ROUGHNESS TOLERANCE

						PFL IN YEARS (1977 TRAFFIC)										
						GOVERNED BY DEF/DI							GOVERNED BY STR/MT			
FACILITY	STATION FROM-TO	VEL	NDT/3 ESUB NORM	NDT/3 ESUB WET	PFLPAV	DI .12G NORM	.18G NORM	.25G NORM	.12G WET	.18G WET	.25G WET	IMPACT	.18G NORM	.30G NORM	.18G WET	.30G WET
RW 1L-19R	0.- 8.	145.	14645.	8787.	18 OC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	4.84	4.02	0.58
RW 1L-19R	8.- 30.	145.	10799.	6479.	18 OC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	1.37	1.20	0.15
RW 1L-19R	30.- 50.	145.	10799.	6479.	18 OC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	0.88	0.72	0.10
RW 1L-19R	50.- 78.	145.	13691.	8215.	18 OC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	2.39	1.92	0.29
RW 1L-19R	78.-108.	145.	13691.	8215.	18 OC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	3.19	2.93	0.39
TW A	0.- 31.	50.	14445.	8667.	10 CC4	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	1.46
TW A	31.- 40.	50.	10916.	6550.	10 CC4	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	3.49	3.18	0.47
TW A	40.- 90.	50.	10916.	6550.	10 CC4	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	2.28	2.08	0.31
TW A	90.-108.	50.	18606.	11164.	10 CC4	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	2.51
RW 9L-27R	0.- 6.	145.	20705.	12423.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	0.98	0.96	0.11
RW 9L-27R	6.- 28.	145.	11348.	6809.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.63	0.07	0.07	0.01
RW 9L-27R	28.- 67.	145.	11348.	6809.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.36	0.04	0.04	0.00
RW 9L-27R	67.- 89.	145.	11348.	6809.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.40	0.04	0.04	0.00
RW 9L-27R	89.- 95.	145.	15963.	9578.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		1.71	0.18	0.18	0.02
TW C	0.- 15.	50.	14852.	8911.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.62	0.08	0.07	0.01
TW C	15.- 26.	50.	14852.	8911.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.97	0.13	0.11	0.01
TW C	26.- 41.	50.	8183.	4910.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.08	0.01	0.01	0.00
TW C	41.- 68.	50.	10243.	6146.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.27	0.03	0.03	0.00
TW C	68.- 88.	50.	14325.	8595.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		1.17	0.15	0.13	0.01
TW C	88.- 95.	50.	22739.	13643.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	1.09	0.96	0.12
TW D	39.- 55.	50.	11173.	6707.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.67	0.08	0.07	0.01
TW B	17.- 38.	50.	17548.	10529.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	0.80	0.67	0.08
TW A	4.- 72.	50.	12961.	7777.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.73	0.09	0.08	0.01

KANSAS CITY INTERNATIONAL AIRPORT - FAA CENTRAL REGION

SUMMARY OF PRESENT FUNCTIONAL LIFE

AS MEASURED BY PROGRESSIVE DETERIORATION OF EXISTING
PAVEMENT SURFACE DUE TO ANTICIPATED AIRCRAFT MOVEMENTS

DI =0.12G SMOOTH PAVEMENT SURFACE
DI =0.18G OPERATIONAL SURFACE
DI =0.25G UPPER LIMIT OF ROUGHNESS TOLERANCE

						PFL IN YEARS (1977 TRAFFIC)										
						GOVERNED BY DEF/DI							GOVERNED BY STR/MT			
FACILITY	STATION FROM-TO	VEL	NDT/3 ESUB NORM	NDT/3 ESUB WET	PFLPAV	DI .12G NORM	.18G NORM	.25G NORM	.12G WET	.18G WET	.25G WET	IMPACT	.18G NORM	.30G NORM	.18G WET	.30G WET
TW B	7.- 82.	50.	14575.	8745.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.85	0.11	0.10	0.01
TW C	8.- 80.	50.	18396.	11038.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	0.74	0.65	0.08
XTW A1-A9	1.- 9.	50.	14795.	8677.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.96	0.13	0.11	0.01
XTW STUB	0.- 0.	50.	22892.	13735.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	0.80	0.70	0.09
XTW C9-C1	1.- 8.	50.	13079.	7847.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		1.16	0.15	0.13	0.01
XTW B3-B9	3.- 5.	50.	9266.	5560.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.38	0.04	0.04	0.00
XTW B3-B9	5.- 9.	50.	9266.	5560.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.36	0.04	0.04	0.00
XTW D7-D3	3.- 7.	50.	15715.	9428.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		3.62	0.50	0.39	0.04
XTW F0-F1	0.- 1.	50.	18549.	11130.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	1.45	1.28	0.15
XTW G1-G2	1.- 2.	50.	15068.	9041.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		4.65	0.63	0.51	0.06

LOS ANGELES INTERNATIONAL AIRPORT - FAA WESTERN REGION

NDT INVENTORY FILE

FACILITY	CODE	STA-FROM	STA-TO	DRAINAGE AT TEST	EPAV NORM	EPAV WET	ESUB NORM	ESUB WET	PFLPAV
1	RW 25R-7L	0.0	5.00	NORM	117445.	84826.	21453.	12872.	11 CC5
		5.00	20.00	NORM	73597.	52295.	13695.	8217.	9 CC3
		20.00	74.00	NORM	67533.	47751.	15323.	9194.	8 CC2
		74.00	120.90	NORM	24197.	17076.	11403.	6842.	1 AC1
2	RW 25L-7R	0.0	5.00	NORM	126958.	90901.	22183.	13310.	12 CC6
		5.00	35.00	NORM	97544.	66701.	15647.	9388.	11 CC5
		35.00	62.00	NORM	78100.	54808.	14933.	8960.	9 CC3
		62.00	120.00	NORM	27773.	19711.	14001.	8401.	1 AC1
3	RW 24L-6R	0.0	5.00	NORM	98402.	71920.	21990.	13194.	9 CC3
		5.00	83.00	NORM	45099.	33403.	21968.	13181.	2 AC2
		83.00	102.80	NORM	77619.	53507.	11413.	6848.	11 CC5
4	RW 24R-6L	0.0	89.30	NORM	97557.	66708.	15650.	9390.	11 CC5
5	TW F	0.0	116.00	NORM	25250.	17640.	11954.	7172.	1 AC1
6	TW J	0.0	60.00	NORM	82301.	56354.	12218.	7331.	11 CC5
		60.00	80.00	NORM	39941.	28578.	24315.	14589.	1 AC1
		80.00	84.00	NORM	88667.	61261.	12791.	7675.	12 CC6
7	TW K	25.00	80.00	NORM	30288.	21063.	15734.	9441.	1 AC1
		80.00	85.00	NORM	106588.	72937.	16663.	9998.	12 CC6
		85.00	125.00	NORM	51385.	36878.	36694.	22016.	1 AC1
		125.00	130.00	NORM	87483.	63772.	23531.	14119.	8 CC2
8	TW U	0.0	86.00	NORM	74795.	52970.	14039.	8423.	9 CC3
		86.00	100.00	NORM	95085.	65396.	15169.	9101.	11 CC5
9	TW 45	0.0	34.00	NORM	44226.	31961.	29008.	17405.	1 AC1
10	TW 47	0.0	34.00	NORM	38383.	27658.	23192.	13915.	1 AC1
11	TW 49	0.0	34.00	NORM	43485.	31494.	28153.	16892.	1 AC1
12	XTW F-25L	3.00	63.00	NORM	22386.	16078.	10336.	6202.	1 AC1
13	XTW 25L-R	3.00	63.00	NORM	29697.	20751.	15354.	9212.	1 AC1
14	XTW 25R-J	3.00	63.00	NORM	36494.	25482.	5134.	3080.	9 CC3
15	XTW U-24L	33.00	85.00	NORM	40891.	27824.	5844.	3506.	9 CC3
16	XTW 24L-R	33.00	80.00	NORM	65726.	45199.	9175.	5505.	11 CC5
17	TM 7-UA	7.00	30.20	NORM	57040.	40178.	9565.	5739.	9 CC3
18	TM 6-CA	6.00	36.10	NORM	52380.	35483.	8243.	4946.	9 CC3
19	TM 5-WA	5.00	42.20	NORM	50252.	34043.	7764.	4659.	9 CC3
20	TM 4-AA	4.00	32.20	NORM	53956.	37030.	8716.	5230.	9 CC3
21	TM 3-TWA	3.00	42.20	NORM	42669.	29041.	6167.	3700.	9 CC3
22	TM 2-NA	2.00	37.20	NORM	49030.	33408.	7540.	4524.	9 CC3
23	TM AIRPRT	3.00	70.00	NORM	44869.	31191.	6686.	4012.	9 CC3
24	TM M1-FAC	10.00	40.00	NORM	49963.	33893.	7712.	4627.	9 CC3

LOS ANGELES INTERNATIONAL AIRPORT - FAA WESTERN REGION

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DI =0.12G SMOOTH PAVEMENT SURFACE
DI =0.18G OPERATIONAL SURFACE
DI =0.25G UPPER LIMIT OF ROUGHNESS TOLERANCE

						PFL IN YEARS (1978 TRAFFIC)										
						GOVERNED BY DEF/DI							GOVERNED BY STR/MT			
FACILITY	STATION FROM-TO	VEL	NDT/3 ESUB NORM	NDT/3 ESUB WET	PFLPAV	DI .12G NORM	.18G NORM	.25G NORM	.12G WET	.18G WET	.25G WET	IMPACT	.18G NORM	.30G NORM	.18G WET	.30G WET
RW 25R-7L	0.- 5.	145.	21453.	12872.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 25R-7L	5.- 20.	145.	13695.	8217.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.16	0.02	0.02	0.00
RW 25R-7L	20.- 30.	145.	15323.	9194.	8 CC2	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.00	0.00	0.00	0.00
RW 25R-7L	30.- 74.	145.	15323.	9194.	8 CC2	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.00	0.00	0.00	0.00
RW 25R-7L	74.- 96.	145.	11403.	6842.	1 AC1	0.00	0.00	0.79	0.00	0.00	0.11		0.00	0.00	0.00	0.00
RW 25R-7L	96.-121.	145.	11403.	6842.	1 AC1	0.00	0.07	>5.00	0.00	0.02	2.18		0.00	0.00	0.00	0.00
RW 25L-7R	0.- 5.	145.	22183.	13310.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 25L-7R	5.- 30.	145.	15647.	9388.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 25L-7R	30.- 35.	145.	15647.	9388.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 25L-7R	35.- 62.	145.	14933.	8960.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		1.43	0.20	0.16	0.02
RW 25L-7R	62.- 95.	145.	14001.	8401.	1 AC1	0.00	0.02	>5.00	0.00	0.01	0.96		0.02	0.00	0.00	0.00
RW 25L-7R	95.-120.	145.	14001.	8401.	1 AC1	0.00	0.16	>5.00	0.00	0.06	>5.00		0.18	0.02	0.00	0.00
RW 24L-6R	0.- 5.	145.	21990.	13194.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		1.66	0.25	0.23	0.03
RW 24L-6R	5.- 30.	145.	21968.	13181.	2 AC2	0.00	0.67	>5.00	0.00	0.27	>5.00		>5.00	>5.00	>5.00	>5.00
RW 24L-6R	30.- 78.	145.	21968.	13181.	2 AC2	0.00	0.67	>5.00	0.00	0.27	>5.00		>5.00	>5.00	>5.00	>5.00
RW 24L-6R	78.- 83.	145.	21968.	13181.	2 AC2	0.03	>5.00	>5.00	0.02	4.48	>5.00		>5.00	>5.00	>5.00	>5.00
RW 24L-6R	83.-103.	145.	11413.	6848.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 24R-6L	0.- 30.	145.	15650.	9390.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 24R-6L	30.- 64.	145.	15650.	9390.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
RW 24R-6L	64.- 89.	145.	15650.	9390.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
TW F	0.-116.	50.	11954.	7172.	1 AC1	0.22	>5.00	>5.00	0.05	>5.00	>5.00		0.00	0.00	0.00	0.00
TW J	0.- 60.	50.	12218.	7331.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	4.72	4.02	0.75
TW J	60.- 80.	50.	24315.	14589.	1 AC1	0.20	>5.00	>5.00	0.05	>5.00	>5.00		>5.00	>5.00	0.03	0.00
TW J	80.- 84.	50.	12791.	7675.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00

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DI =0.12G SMOOTH PAVEMENT SURFACE
DI =0.18G OPERATIONAL SURFACE
DI =0.25G UPPER LIMIT OF ROUGHNESS TOLERANCE

FACILITY	STATION FROM-TO	VEL	NDT/3 ESUB NORM	NDT/3 ESUB WET	PFLPAV/	GOVERNED BY DEF/DI: DI .12G NORM	.18G NORM	.25G NORM	.12G WET	.18G WET	.25G WET	IMPACT	GOVERNED BY STR/MT: .18G NORM	.30G NORM	.18G WET	.30G WET
TW K	25.- 80.	50.	15724.	9441.	1 AC1	0.04	>5.00	>5.00	0.01	>5.00	>5.00		0.14	0.02	0.00	0.00
TW K	80.- 85.	50.	16665.	9998.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
TW K	85.-125.	50.	36694.	22016.	1 AC1	>5.00	>5.00	>5.00	1.17	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
TW K	125.-130.	50.	23531.	14119.	8 CC2	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		1.00	0.13	0.07	0.01
TW U	0.- 40.	50.	14039.	6423.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.21	0.05	0.02	0.00
TW U	40.- 80.	50.	14039.	6423.	9 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	1.94	1.20	0.18
TW U	80.-130.	50.	15169.	9101.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
TW 45	0.- 34.	50.	29008.	17405.	1 AC1	0.73	>5.00	>5.00	0.21	>5.00	>5.00		>5.00	>5.00	4.20	0.77
TW 47	0.- 34.	50.	23192.	13915.	1 AC1	0.23	>5.00	>5.00	0.07	>5.00	>5.00		>5.00	>5.00	0.02	0.00
TW 49	0.- 34.	50.	28153.	16892.	1 AC1	1.58	>5.00	>5.00	0.47	>5.00	>5.00		>5.00	>5.00	4.94	0.85
XTW F-25L	3.- 63.	50.	10336.	6202.	1 AC1	0.11	>5.00	>5.00	0.04	>5.00	>5.00		0.00	0.00	0.00	0.00
XTW 25L-R	3.- 63.	50.	15354.	9212.	1 AC1	0.17	>5.00	>5.00	0.04	>5.00	>5.00		0.31	0.04	0.00	0.00
XTW 25R-J	3.- 63.	50.	5134.	5080.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.00	0.00	0.00	0.00
XTW U-24L	33.- 85.	50.	5844.	3506.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.01	0.00	0.00	0.00
XTW 24L-K	33.- 80.	50.	9175.	5505.	11 CC5	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
TW 7-UA	7.- 30.	50.	9565.	5739.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.07	0.01	0.01	0.00
TW 6-CA	0.- 36.	50.	8243.	4946.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.07	0.01	0.01	0.00
TW 5-WJ	5.- 42.	50.	7764.	4659.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.05	0.01	0.00	0.00

LOS ANGELES INTERNATIONAL AIRPORT - FAA WESTERN REGION

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DI =0.12G SMOOTH PAVEMENT SURFACE
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						PFL IN YEARS (1978 TRAFFIC)										
						GOVERNED BY DEF/DI							GOVERNED BY STR/MT			
FACILITY	STATION FROM-TO	VEL	NDT/3 ESUB NORM	NDT/3 ESUB WET	PFLPAV	DI .12G NORM	.18G NORM	.25G NORM	.12G WET	.18G WET	.25G WET	IMPACT	.18G NORM	.30G NORM	.18G WET	.30G WET
TW 4-AA	4.- 32.	50.	8716.	5230.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.06	0.01	0.01	0.00
TW 3-TWA	3.- 42.	50.	6167.	3700.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.02	0.00	0.00	0.00
TW 2-[illegible]A	2.- 57.	50.	7540.	4524.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.07	0.01	0.01	0.00
TW AIRPRT	3.- 70.	50.	6686.	4012.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.04	0.00	0.00	0.00
TW MT-[illegible]	10.- 40.	50.	7712.	4627.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.08	0.01	0.01	0.00

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NDT INVENTORY FILE

FACILITY	CODE	STA-FROM	STA-TO	DRAINAGE AT TEST	EPAV NORM	EPAV WET	ESUB NORM	ESUB WET	PFLPAV
1	RW 18R36L	72.00	160.00	NORM	118379.	85672.	20090.	12054.	12 CC6
2	RW 18L36R	77.00	131.00	NORM	124427.	89370.	21595.	12957.	12 CC6
		131.00	160.00	NORM	79975.	58144.	12065.	7239.	17 OC4
3	RW 9-27	70.00	82.00	NORM	42647.	29769.	4618.	2771.	15 OC2
		82.00	140.00	NORM	36521.	25715.	4571.	2743.	14 OC1
4	TW E	72.00	132.00	NORM	92403.	68152.	19981.	11988.	9 CC3
		132.00	157.00	NORM	52709.	39043.	28257.	16954.	2 AC2
5	TW H	77.00	118.00	NORM	117558.	80955.	16276.	9765.	20 OC7
		118.00	126.00	NORM	77629.	54735.	9146.	5488.	20 OC7
		126.00	145.00	NORM	111805.	77514.	15206.	9124.	20 OC7
6	TW A	77.00	160.00	NORM	34011.	24741.	19489.	11693.	1 AC1
7	TW C	101.00	139.00	NORM	30127.	20979.	15632.	9379.	1 AC1
8	TW G	70.00	107.00	WET	87265.	62319.	18040.	10824.	9 CC3
		107.00	117.00	NORM	39996.	28750.	5260.	3156.	14 OC1
		117.00	140.00	NORM	29070.	21061.	10759.	6456.	2 AC2
9	TW J	56.00	85.00	NORM	124248.	89262.	21553.	12932.	12 CC6
10	XTW @36L	6.00	53.00	NORM	35394.	24706.	4929.	2957.	9 CC3
11	HP 18R	154.40	158.40	NORM	74518.	58421.	56072.	33643.	2 AC2
12	XTW @36R	4.70	157.40	NORM	35221.	25813.	10823.	6494.	3 AC3
13	HP 36R	95.80	100.80	NORM	32210.	22260.	3737.	2242.	14 OC1
14	XTW@RW09	22.30	114.00	NORM	26539.	19663.	2843.	1706.	14 OC1
15	TW F	4.70	17.40	NORM	43340.	30648.	5818.	3491.	14 OC1
16	TW ACCESS	76.00	90.50	NORM	38075.	27475.	22959.	13775.	1 AC1
17	TM B	129.00	137.00	NORM	100372.	68679.	15251.	9151.	12 CC6
18	TM C	8.00	149.00	NORM	135392.	95934.	23982.	14389.	12 CC6
19	TM D	68.50	148.30	NORM	116112.	83255.	19485.	11691.	12 CC6
20	TM F	128.50	139.50	NORM	114323.	81242.	18991.	11394.	12 CC6
21	RW 18REXT	160.10	180.00	NORM	9141.	5485.	9141.	5485.	0 SUB
22	XTW NAPRN	71.30	73.80	NORM	61259.	41298.	7675.	4605.	12 CC6

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SUMMARY OF PRESENT FUNCTIONAL LIFE

AS MEASURED BY PROGRESSIVE DETERIORATION OF EXISTING
PAVEMENT SURFACE DUE TO ANTICIPATED AIRCRAFT MOVEMENTS

DI =0.12G SMOOTH PAVEMENT SURFACE
DI =0.18G OPERATIONAL SURFACE
DI =0.25G UPPER LIMIT OF ROUGHNESS TOLERANCE

						PFL IN YEARS (1978 TRAFFIC)									
						GOVERNED BY DEF/DI						GOVERNED BY STR/MT			
FACILITY	STATION FROM-TO	VEL	NDT/3 ESUB NORM	NDT/3 ESUB WET	PFLPAV	DI .12G NORM	.18G NORM	.25G NORM	.12G WET	.18G WET	.25G WET	IMPACT .18G NORM	.30G NORM	.18G WET	.30G WET
RW 18R36L	72.-102.	145.	20090.	12054.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
RW 18R36L	102.-129.	145.	20090.	12054.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
RW 18R36L	129.-159.	145.	20090.	12054.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
RW 18L36R	77.-107.	145.	21595.	12957.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
RW 18L36R	107.-130.	145.	21595.	12957.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
RW 18L36R	130.-131.	145.	21595.	12957.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
RW 18L36R	131.-160.	145.	12065.	7239.	17 OC4	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	0.37	0.03	0.03	0.00
RW 9-27	70.- 82.	145.	4618.	2771.	15 OC2	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	0.00	0.00	0.00	0.00
RW 9-27	82.-140.	145.	4571.	2743.	14 OC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	0.00	0.00	0.00	0.00
TW E	72.-114.	50.	19981.	11989.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	3.52	0.53	0.50	0.06
TW E	114.-132.	50.	19981.	11988.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	1.59	0.24	0.23	0.03
TW E	132.-142.	50.	28257.	16954.	2 AC2	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW E	142.-157.	50.	28257.	16954.	2 AC2	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW H	77.-108.	50.	16276.	9765.	20 OC7	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW H	108.-118.	50.	16276.	9765.	20 OC7	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW H	118.-126.	50.	9146.	5488.	20 OC7	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW H	126.-145.	50.	15206.	9124.	20 OC7	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00
TW A	77.-160.	50.	19489.	11693.	1 AC1	1.89	>5.00	>5.00	0.69	>5.00	>5.00	>5.00	>5.00	0.00	0.00
TW C	101.-139.	50.	15632.	9379.	1 AC1	1.57	>5.00	>5.00	0.32	>5.00	>5.00	1.27	0.13	0.00	0.00
TW D	70.-107.	50.	18040.	10824.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	1.09	0.94	0.11
TW D	107.-117.	50.	5260.	3156.	14 OC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	0.00	0.00	0.00	0.00
TW D	117.-140.	50.	10759.	6456.	2 AC2	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00	3.37

TAMPA INTERNATIONAL AIRPORT - FAA SOUTHERN REGION

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DI =0.18G OPERATIONAL SURFACE
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						PFL IN YEARS (1978 TRAFFIC)										
						GOVERNED BY DEF/DI							GOVERNED BY STR/MT			
FACILITY	STATION FROM-TO	VEL	NDT/3 ESUB NORM	NDT/3 ESUB WET	PFLPAV	DI .12G NORM	.18G NORM	.25G NORM	.12G WET	.18G WET	.25G WET	IMPACT	.18G NORM	.30G NORM	.18G WET	.30G WET
TW J	56.- 85.	50.	21553.	12932.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
XTW 236L	6.- 53.	50.	4929.	2957.	9 CC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.01	0.00	0.00	0.00
HP 18R	154.-158.	50.	56072.	33643.	2 AC2	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
XTW 236R	5.-157.	50.	10823.	6494.	3 AC3	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	1.26	0.20
HP 36R	96.-101.	50.	3737.	2242.	14 DC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.00	0.00	0.00	0.00
XTWEKW09	22.-114.	50.	2843.	1706.	14 DC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.00	0.00	0.00	0.00
TW F	5.- 17.	50.	5818.	3491.	14 DC1	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		0.00	0.00	0.00	0.00
TW ACCESS	76.- 91.	50.	22959.	13775.	1 AC1	1.47	>5.00	>5.00	0.45	>5.00	>5.00		>5.00	>5.00	0.03	0.00
TW B	129.-137.	50.	15251.	9151.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
TW C	8.-149.	50.	23982.	14389.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
TW D	69.-148.	50.	19485.	11691.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
TW E	129.-140.	50.	18991.	11394.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00
XTW NAPRN	72.- 74.	50.	7675.	4605.	12 CC6	>5.00	>5.00	>5.00	>5.00	>5.00	>5.00		>5.00	>5.00	>5.00	>5.00

APPENDIX 3 SENSITIVITY ANALYSIS OF PAVEMENT THICKNESS EFFECTED BY AIRCRAFT LANDING GEAR DESIGN

CONTENTS

GENERAL EQUILIBRIUM OF PAVEMENT SYSTEM UNDER AIRCRAFT LANDING GEAR LOAD

GENERAL EQUILIBRIUM OF LAYERED SYSTEM, GELS: $\nabla^2\nabla^2\phi = 0$

BOUSSINESQ SOLUTION FOR ONE LAYER SYSTEM:

$$\phi = B(r^2 + z^2)^{1/2}$$

$$\sigma_z = p[1 - z^3/(a^2 + z^2)^{3/2}]$$

$$w_o = 2pa(1 - \mu^2)/E$$

BURMISTER'S SOLUTION FOR MULTI-LAYER SYSTEM:

$$\phi_i = J_o(mr)(A_i + B_i z)e^{mz} + (C_i + D_i z)e^{-mz}$$

COMPUTER SOLUTION:

$$\begin{vmatrix} \sigma_z \\ w_o \end{vmatrix} = a\int_o^\infty K(\mu_i, E_i)\cdot M(z,\mu_i)\cdot D(z) \begin{vmatrix} A_i \\ B_i \\ C_i \\ D_i \end{vmatrix} J_1(ma)\cdot dm$$

PLATE THEORY Consider only the equilibrium of top layer and also assume that all supporting layers are in equilibrium to be represented by a stiffness factor D. The equilibrium equation is:

$$\nabla^2\nabla^2 w = p/D$$

Thus, the axial or shear forces are not considered in the analysis.

GELS ANALYSIS FOR MULTIPLE WHEEL LOAD The computer will output:

Layer stress $\sigma_z(p, a, h, E, \mu, i, z, x, y)$

Surface deflection $w_o(p, a, h, e, \mu, x, y)$

FUNCTIONAL REQUIREMENTS OF PAVEMENT The limiting conditions are:

Layer stress $\sigma_t(C, N, s, \nu, E, DI)$

Surface deflection $w_z(p, a, N, f, DI, v, h, E, \mu)$

PAVEMENT THICKNESS DESIGN The thickness of pavement layer shall meet:

Limiting layer stress $\sigma_z = \sigma_t$

Limiting surface deflection $w_o = w_z$

SENSITIVITY ANALYSIS OF PAVEMENT THICKNESS

AIRCRAFT TRAFFIC MOVEMENTS Aircraft traffic movement is a functional requirement which governs the decision on limiting layer stress and surface deflection, such as N factor in computing σ_t and w_z. Based on the full size pavement tests at Newark Airport, the progressive accumulation of surface deformation and stress deterioration is a function of (1 - C log N) which is similar to the cumulative damage experienced in fatigue tests. Experience also indicates that for reliable pavement analysis, the desirable range of N-value is between 10^4 to 10^6 aircraft movements. Computer

results of L-1011-1 sensitivity analysis are shown in MLG/PLOTs 1 to 3 for asphaltic concrete and portland cement concrete pavements.

MAXIMUM TAKEOFF WEIGHT The effect of aircraft landing gear load is indicated by the factors (p,a,h,E,μ,x,y) in which (p,a) represent the static wheel load; (x,y) are the coordinates of gear-wheel configuration; and (h,E,μ) are the physical characteristics of layer system. For limiting stress criteria, the wheel loads have no influence on the determination of σ_t. The pavement thickness design depends on the stress computation, σ_z by GELS. For limiting surface deflection, the allowable deflection w_z is a function of (p,a,N,f,DI,v,E,μ,h). Thus, pavement thickness design will vary significantly with aircraft velocity, v, (145 kt on runway and 50 kt on taxiway are used in the analysis) and the E-value of subgrade. On MLG/PLOTs 4 to 6, the computed effect of aircraft loads are indicated for asphalt and concrete pavements.

NATURAL FREQUENCY OF AIRCRAFT AT TIRE-PAVEMENT INTERFACE The riding quality induced by the pavement, as indicated by the aircraft vibration, is closely related to the influence of natural frequency, f; of dynamic response, DI; and of crossing velocity, v, of an operating aircraft. Aircraft operating characteristics affect only the determination of deflection tolerance and have no influence on theoretical stress/deflection computation or on the limiting stress analysis. Since the limiting deflection analysis is also governed by pavement layer properties (h,E,μ) and particularly the subgrade E-value, the high E-value of these layers will have an overriding effect on (f,DI,v) in determining the limit of surface deflection. On MLG/PLOT 7, the limiting deflection criterion is not a governing condition for asphalt pavement if the subgrade E-value is better than 9,000 psi. For concrete pavements, as shown on MLG/PLOTs 8 and 9, the high E-value of concrete layer also excludes the limiting deflection as a governing condition.

TIRE PRESSURE In aircraft load analysis, the wheel load is expressed by $P = \pi pa^2$ in which p is the tire pressure and a is the radius of contact area. For a constant wheel load, the increase of tire pressure means the decrease of contact radius or vise versa. The self-compensating effect between p and a will result in a minor variation in thickness design. MLG/PLOTs 10 to 12 confirm this minor variation.

WHEEL AND AXLE SPACINGS By using the principle of superposition, the computer determines the layer stress and surface deflection of pavement system under the influence of multiple wheel aircraft load expressed by coordinates x and y. The multi-wheel loads have no significant influence on the development of stress or on deflection limits of pavement system. In the theoretical analysis, if x or y is greater than 3.5a, approx. 32 inches for L-1011-1, the effect of superposition is not significant. MLG/PLOTs 13 to 18 demonstrate such relationship.

RUNWAY NAVIGATION SYSTEM Regarding aircraft traffic movement, the progressive deterioration of pavement performance is related to cumulative aircraft movements, N. In computer analysis, the aircraft movements are refined into effective load repetitions which is a function of probability distribution of wheel loads as influenced by the navigation system installed on the pavement. For normal/visual operation, aircraft load will be distributed in a much wider band than under certerline lights and ILS rule. Therefore, the pavement will be subject to more load repetitions if ILS rule and centerline lights are operational. The effects on pavement thickness design are shown on MLG/PLOT 19.

PAVEMENT COMPOSITION The physical properties of pavement layers are expressed by parameters h, E and μ. The thickness of the most important layer is usually designed by stress or deflection analysis. The Poisson's ratio normally has no significant effect on the outcome of design analysis. Therefore, the most significant factor in thickness design is the E-value of pavement layer. In MLG/PLOT 20, the AC/NOR represents the asphalt pavement in northern regions as having an E-value of 200,000 psi, while the AC/SOU of the same asphalt pavement in southern regions has an E-value of 100,000 psi. The thickness requirements of these pavements are significantly different. Similar computations were made for concrete pavement on CTB and aggregate base which have an E-value of 200,000 and 40,000 psi respectively. The effect of E-value of base course will be reflected in the thickness computation of concrete layer.

CORRELATION WITH CBR OR PCA METHODS CBR method sponsored by WES was developed during the period when Palmer and Barber introduced the classic Boussinesq solution for determining pavement thickness and the Navy's design manual suggested the use of deflection tolerance of 0.15 inch. With the development of a modern computer program, attempts have been made to analyze and compare the CBR method with the layered system. Reliable correlation depends on the degree of accuracy in the following adjustments:
1) The conversion of CBR to E-value which may range from 120 to 1560 having a practical range between 300 to 600;
2) The selection of equivalency factor which may run from 1.7 to 2.3 for converting CBR thickness to realistic layer materials;
3) The increase of limiting 5,000 load coverages in the CBR method to a realistic figure, say 100,000 coverages in 20 year service life.

In MLG/PLOT 21, a conversion equation, E = 500 CBR, and an equivalency factor 2.0 are used to convert the CBR curves as shown on Fig. 7.5. (see L-1011-1 Airplane Characteristics for Airport Planning, CER12013 by Lockheed - California Company, August 1978). Some close correlations can be observed. Similarly, for concrete pavement, if the conversion equation is E = 40 k and tensile stress is assumed to be 400 psi, there is a good correlation with PCA curves as shown on Fig. 7.7 (see same reference CER12013).

SYMBOLS:		
	A,B,C,D	Contants of integration
	a	Radius of tire-pavement contact area
	C	Fatigue coefficient of layer material
	D	Slab stiffness factor

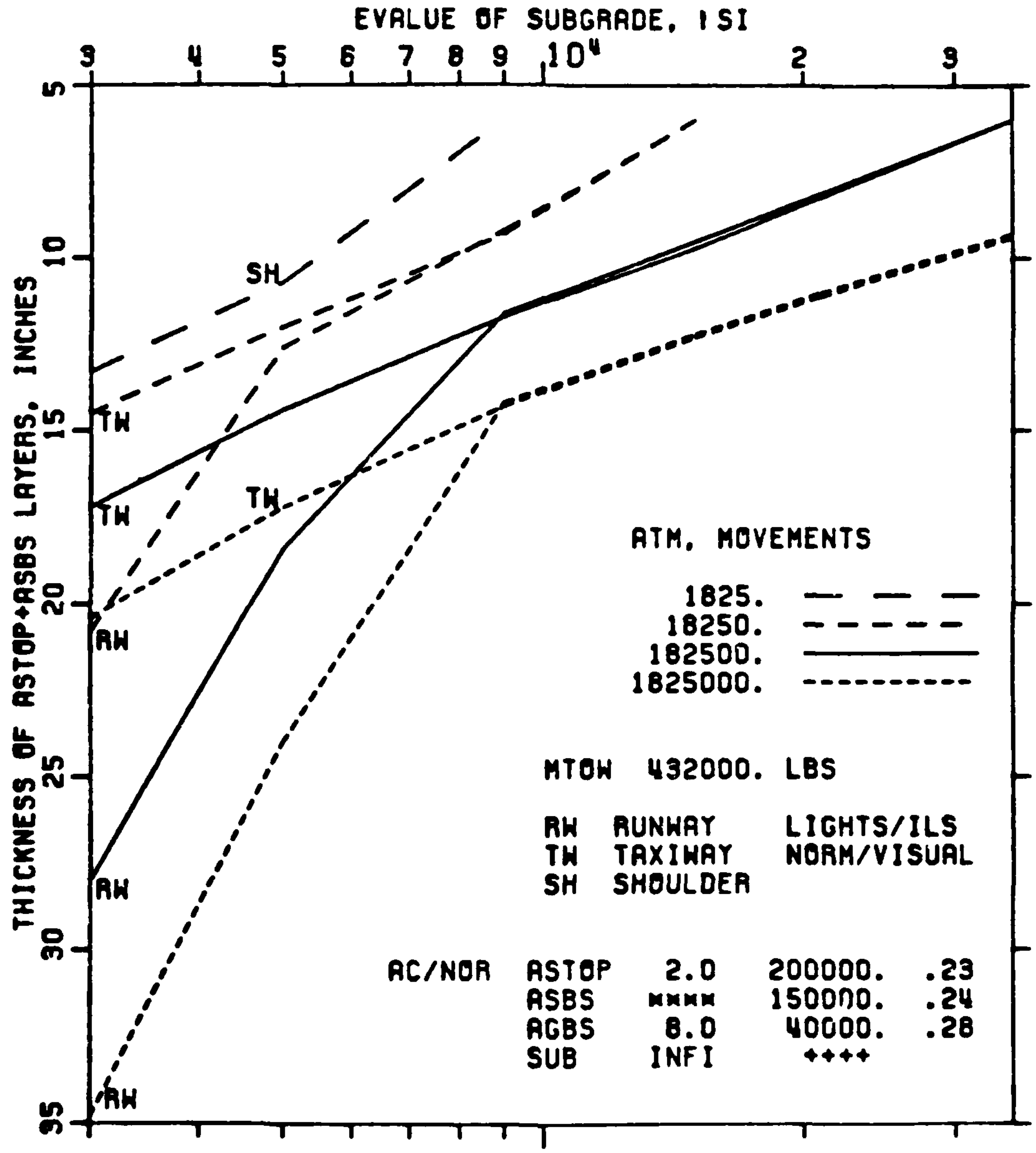
DI	Dynamic response of aircraft
E, μ	Material characteristics of layer component
f	Natural frequency of aircraft at tire pavement interface
h	Thickness of layer component
i	Layer counter
J_o	Bessel function of the first kind of zero order
K	Matrix of Bessel function
M	Matrix of m parameter
m	Arbitrary parameter
N	Load repetitions of aircraft traffic movement
P	Maximum takeoff weight
p	Tire Pressure
r,z	Polar coordinates
s_o	Overstress factor
v	Crossing velocity of aircraft
w_o	Surface deflection of pavement
w_z	Limiting surface deflection
x	Wheel spacing
y	Axle spacing
σ_t	Limiting layer stress
σ_z	Working stress of pavement layer
∇	Differential equation operator
ϕ	Stress function
ν	Coefficient of variance of material strength
NAV	Navigation system on pavement

L1011-1 AIRCRAFT PARAMETERS:

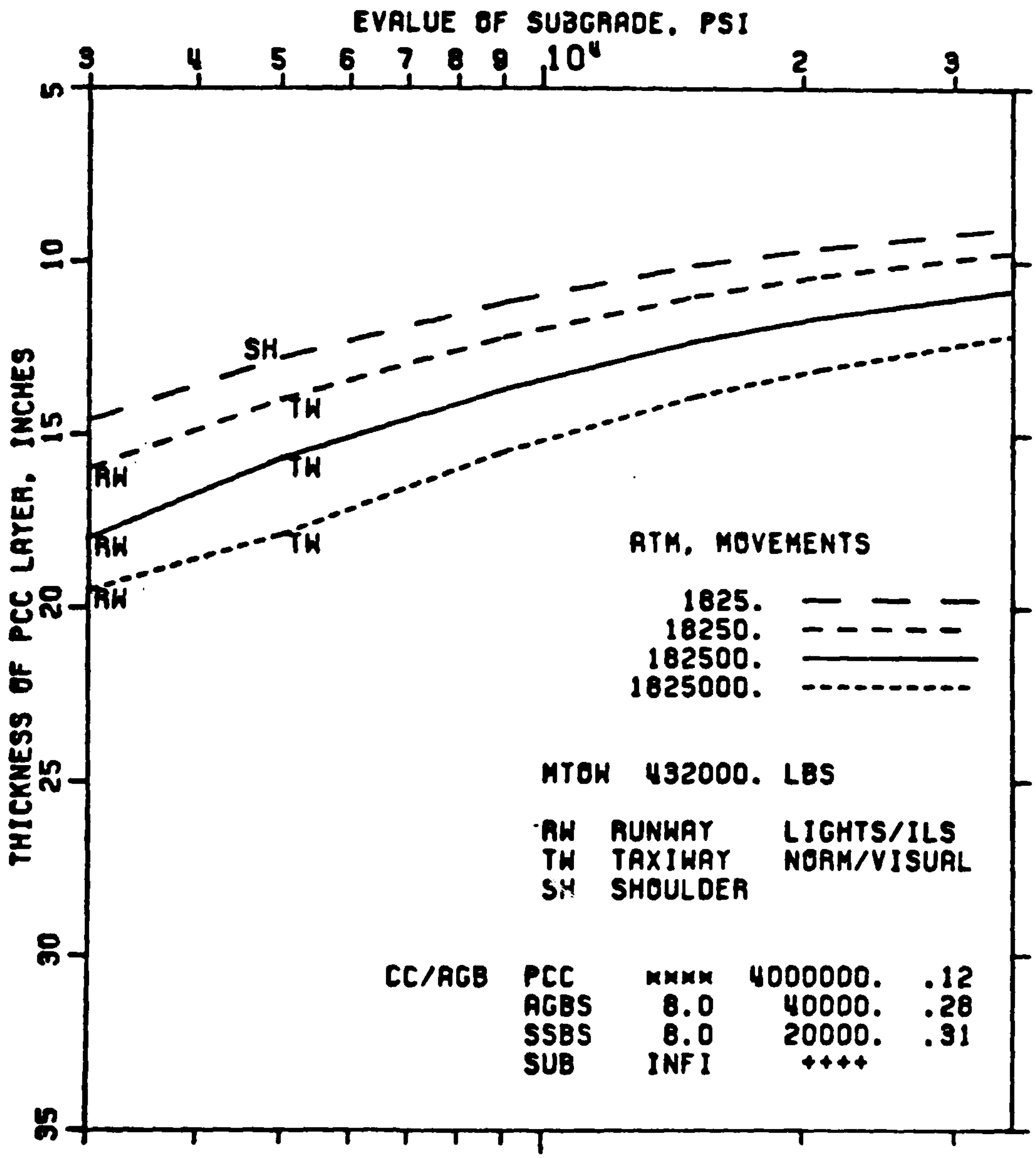
ATM, Movements:	1,825 18,250 182,500* 1,825,000
MTOW, Max. Take-off Wt:	388,800 lbs. 432,000 lbs.* 475,000 lbs.
Frequency (Tire-pavement Interface):	1.0 Hz 1.1 Hz* 1.2 Hz
Tire Pressure:	160 psi 180 psi* 200 psi
Wheel Spacing:	47 inches 52 inches* 57 inches
Axle Spacing:	63 inches 70 inches* 77 inches

* Denotes standard parameters.

SENSITIVITY ANALYSIS OF AIRCRAFT L-1011-1



SENSITIVITY ANALYSIS OF AIRCRAFT L-1011-1



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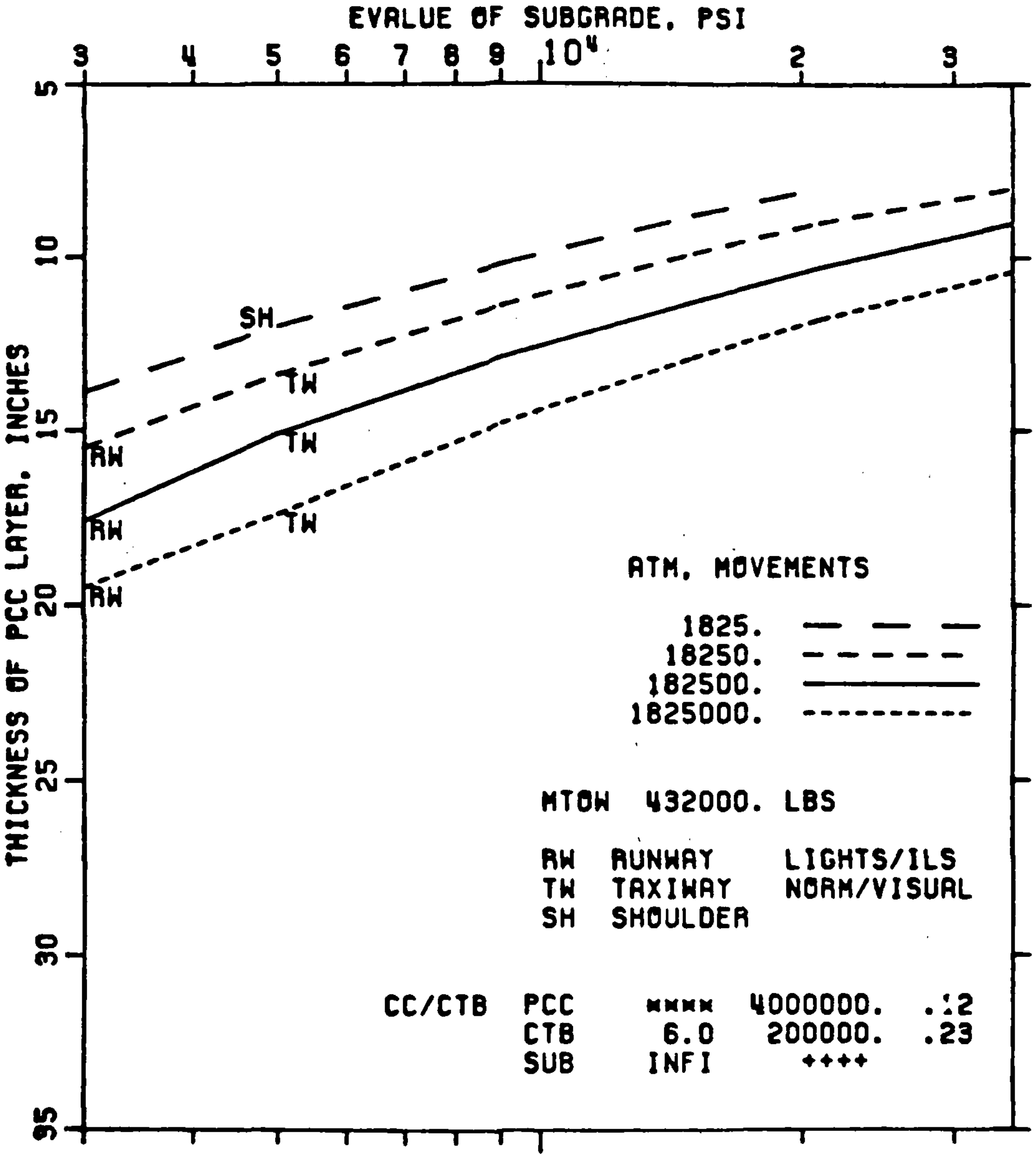

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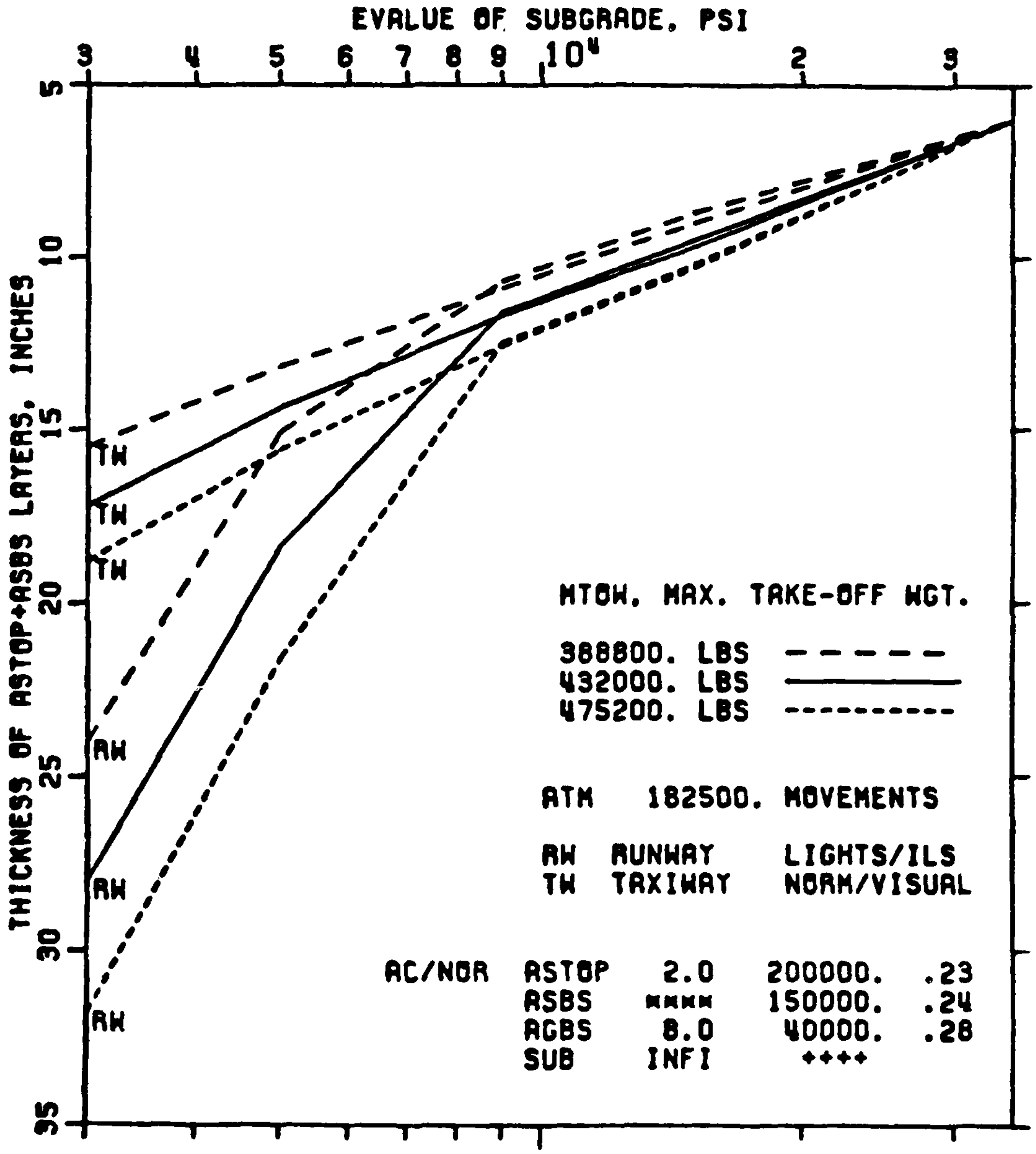

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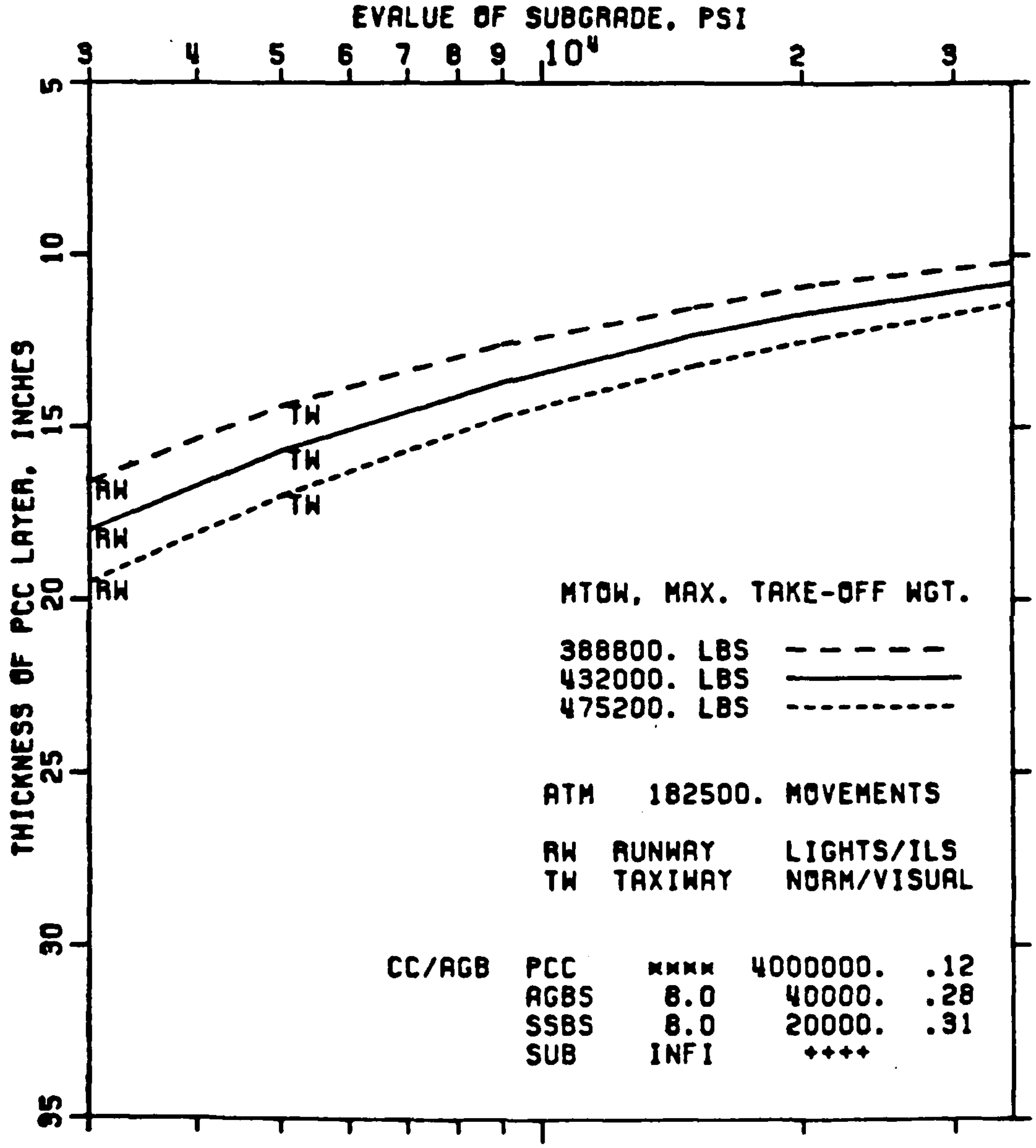

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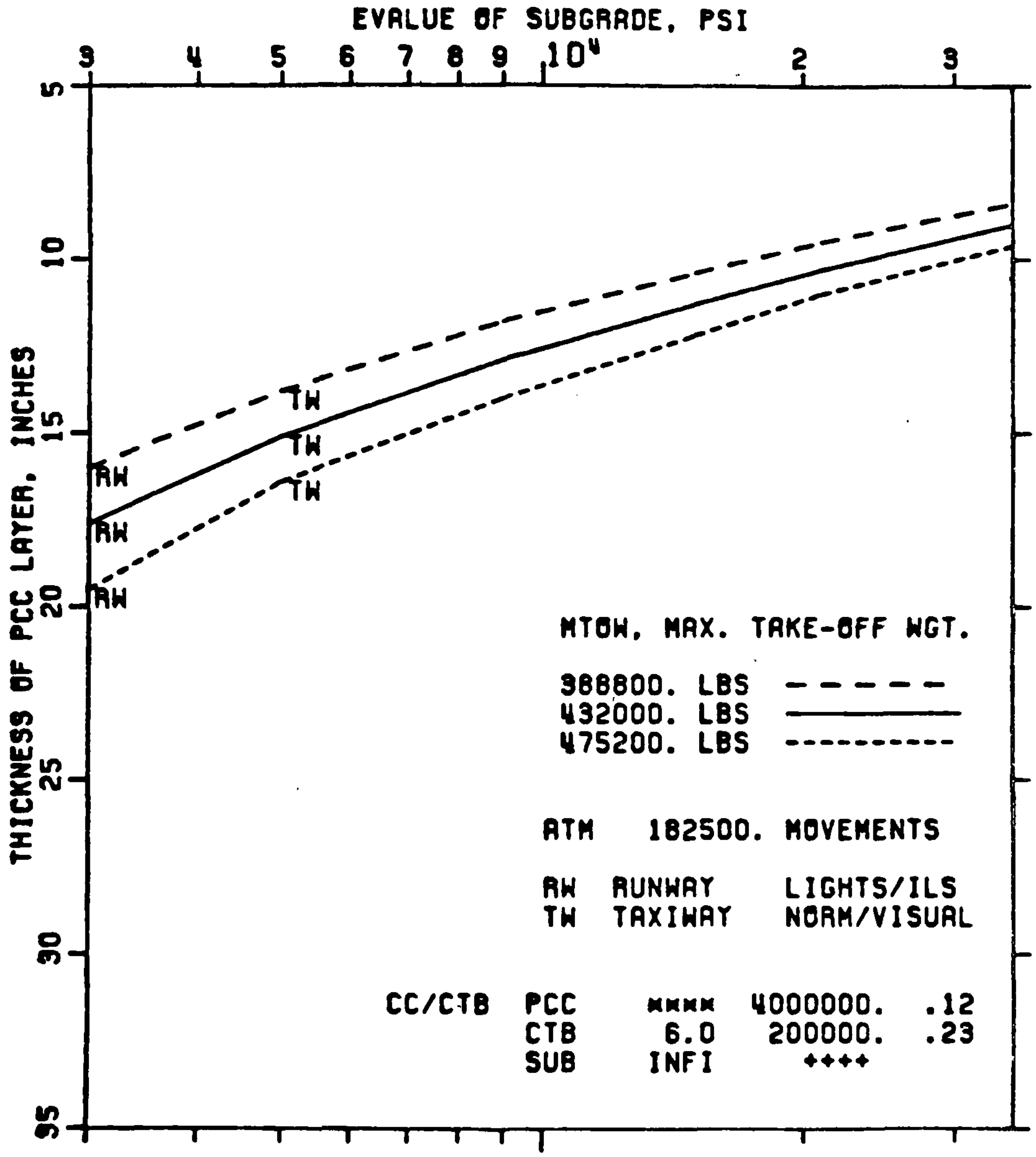

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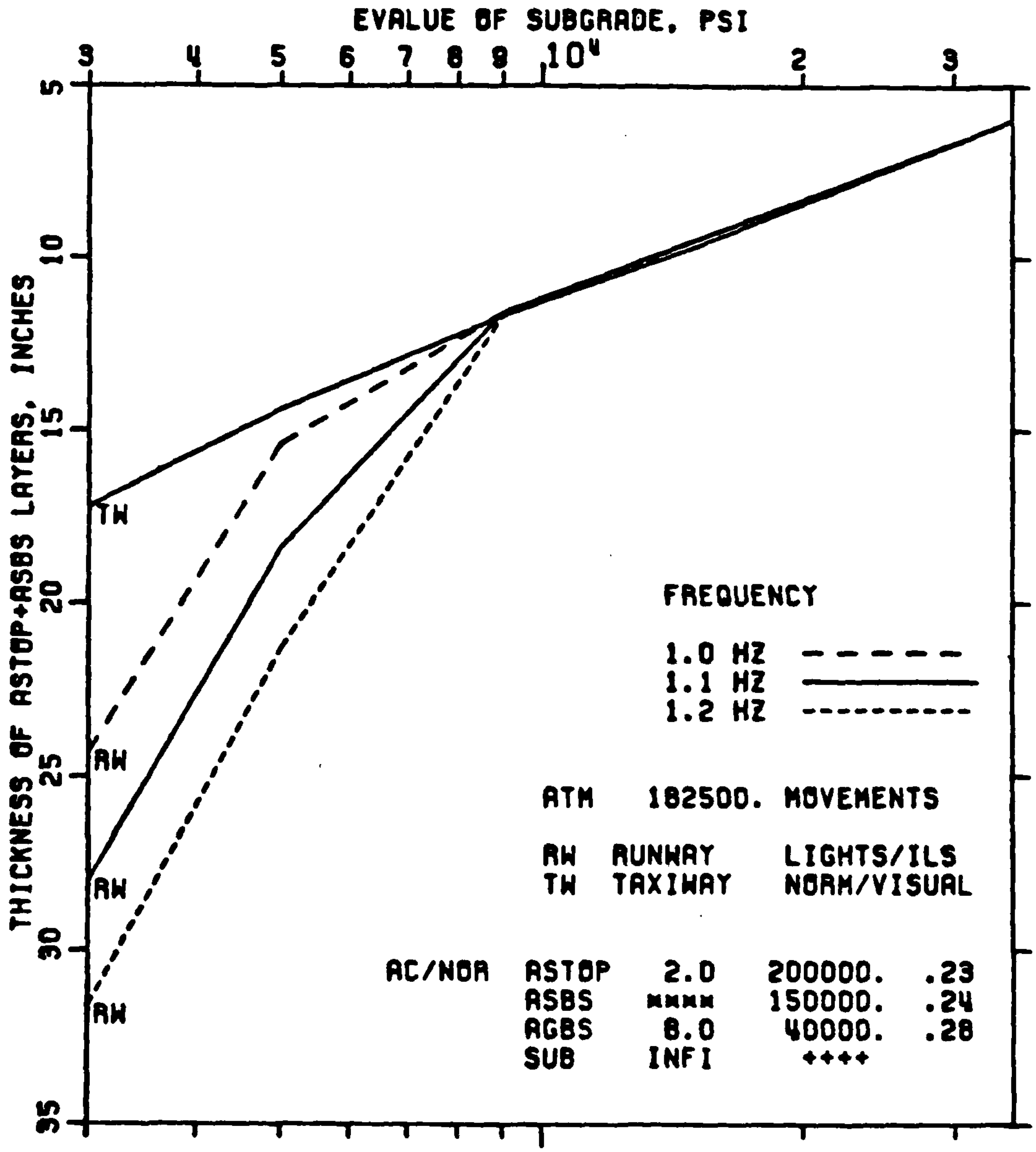

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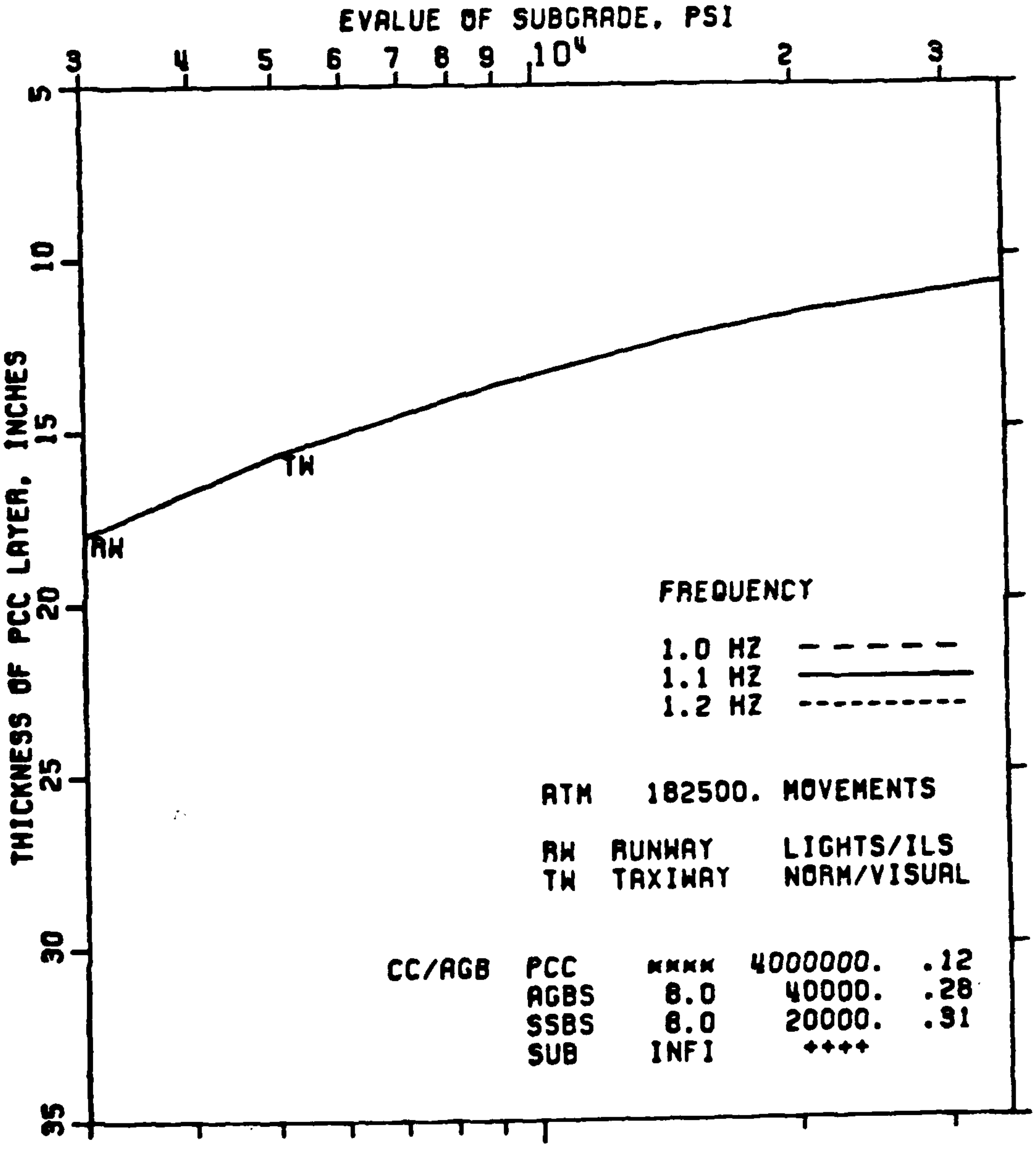

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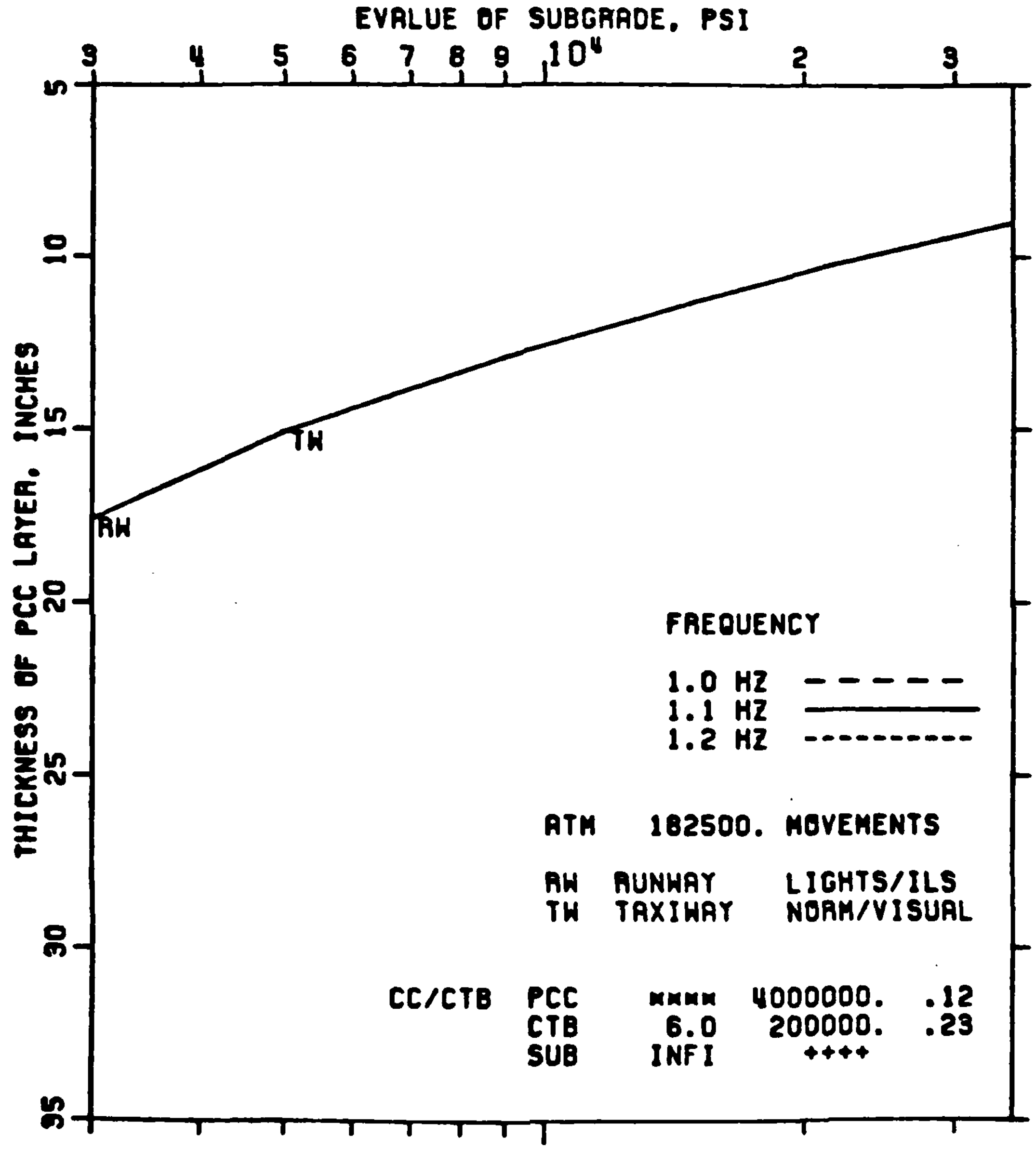
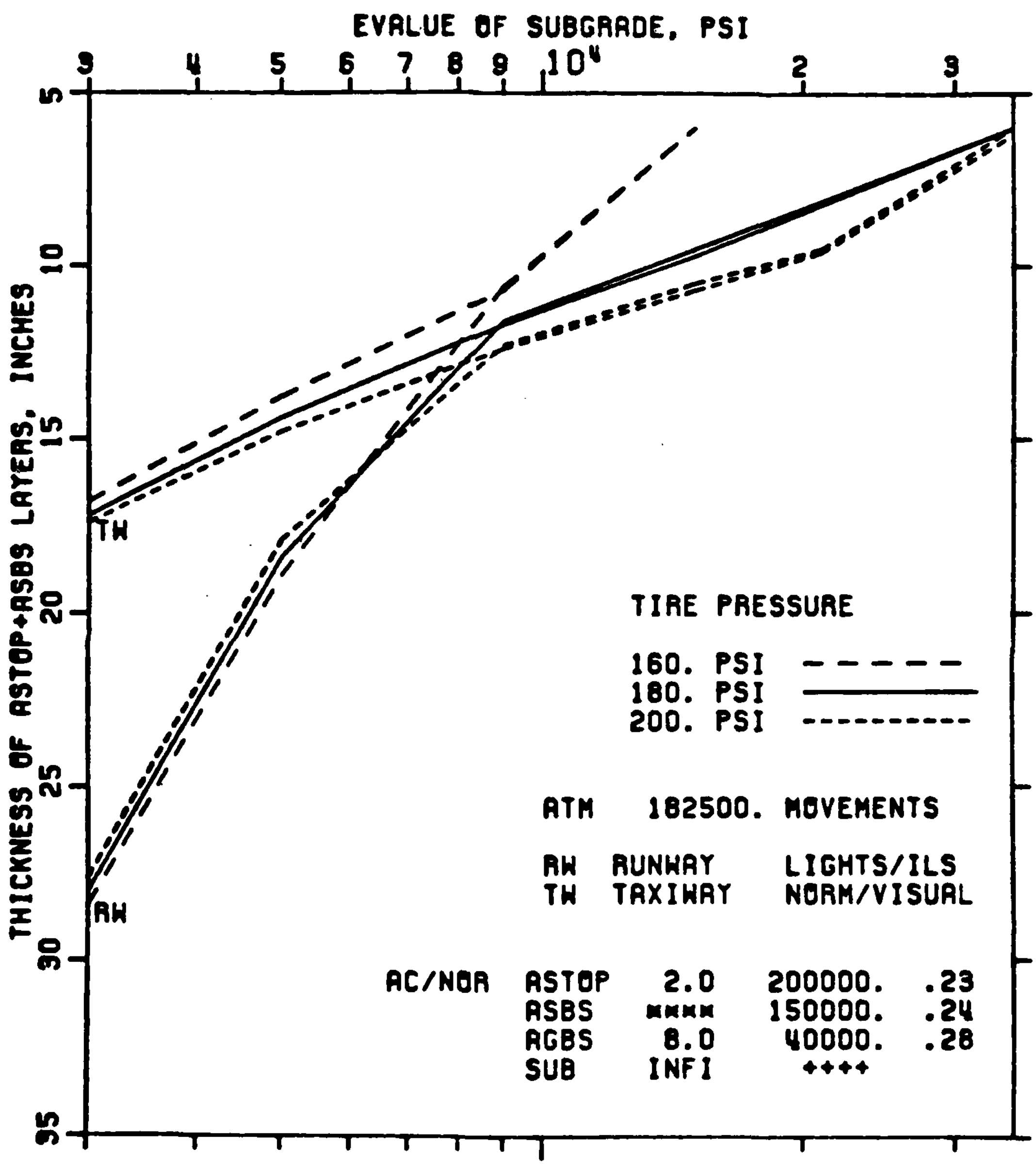


SENSITIVITY ANALYSIS OF AIRCRAFT L-1011-1



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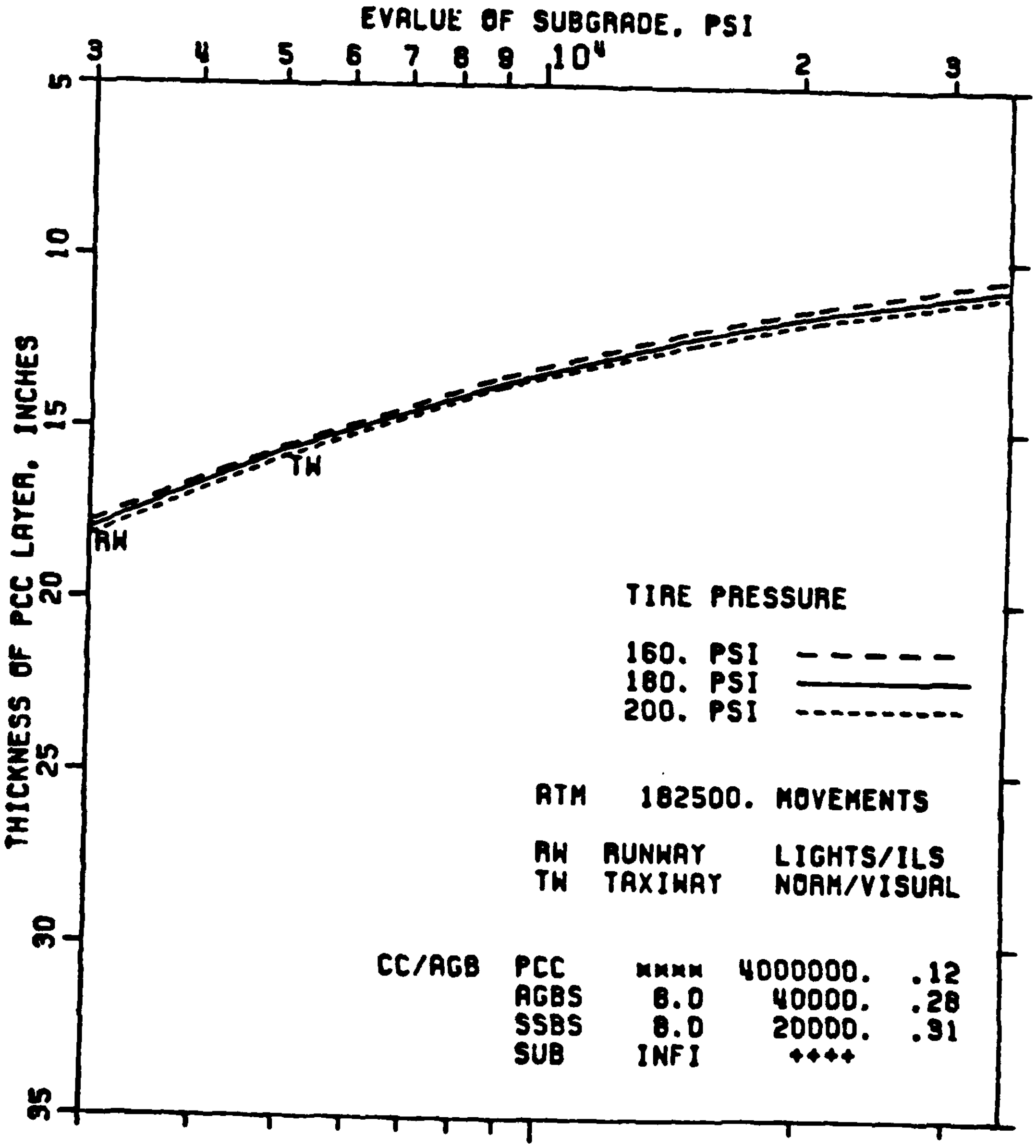

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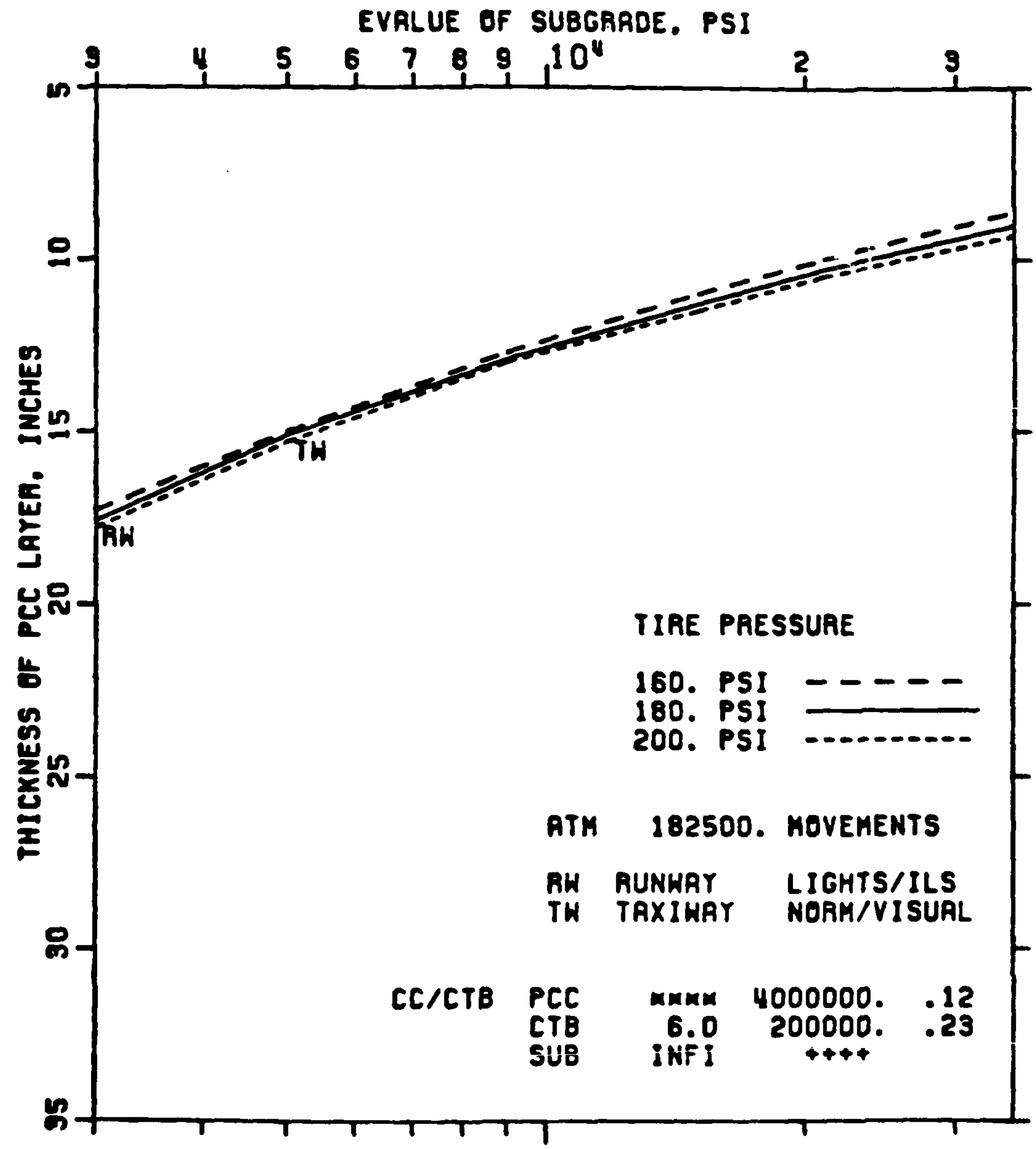

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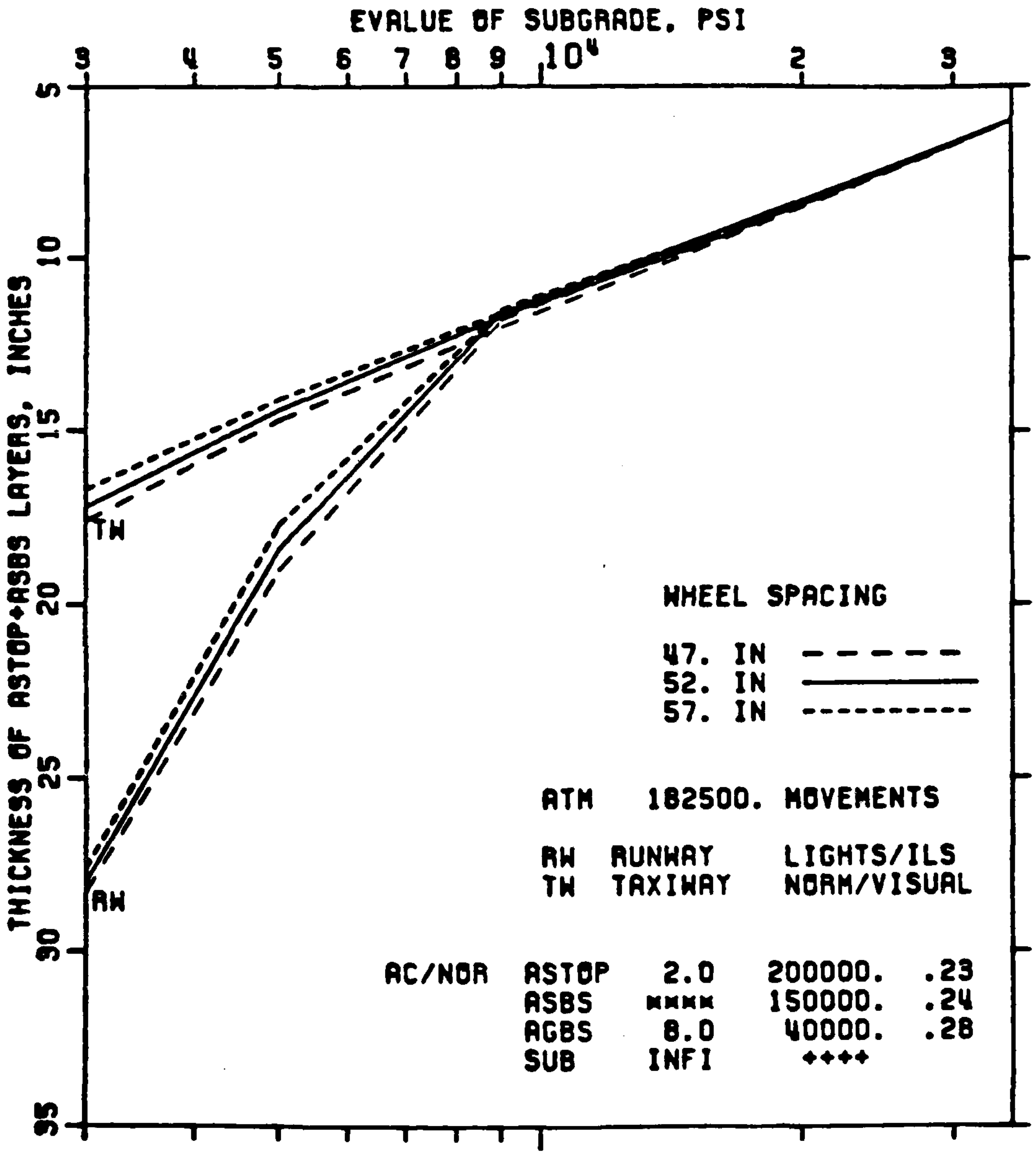

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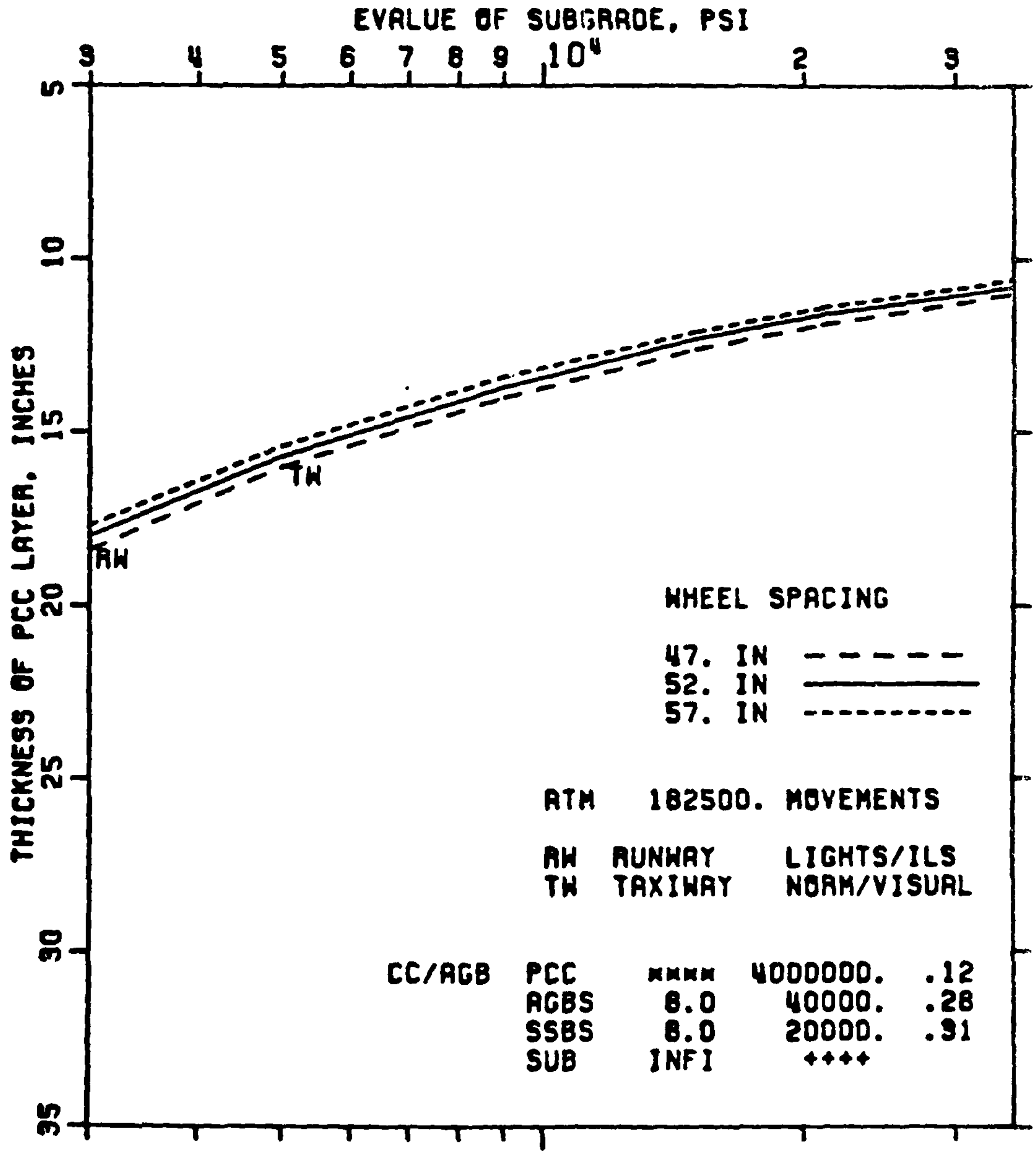

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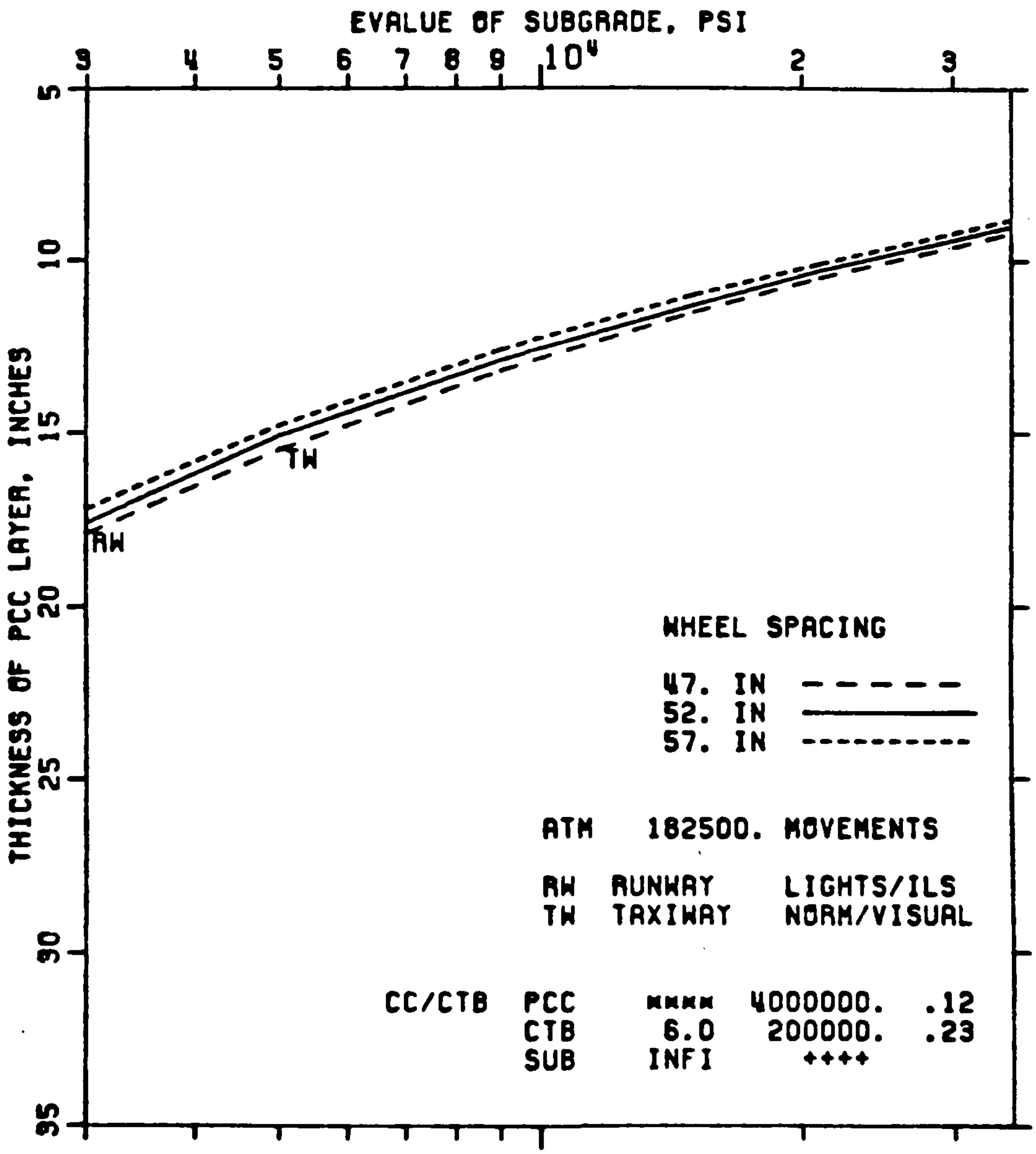

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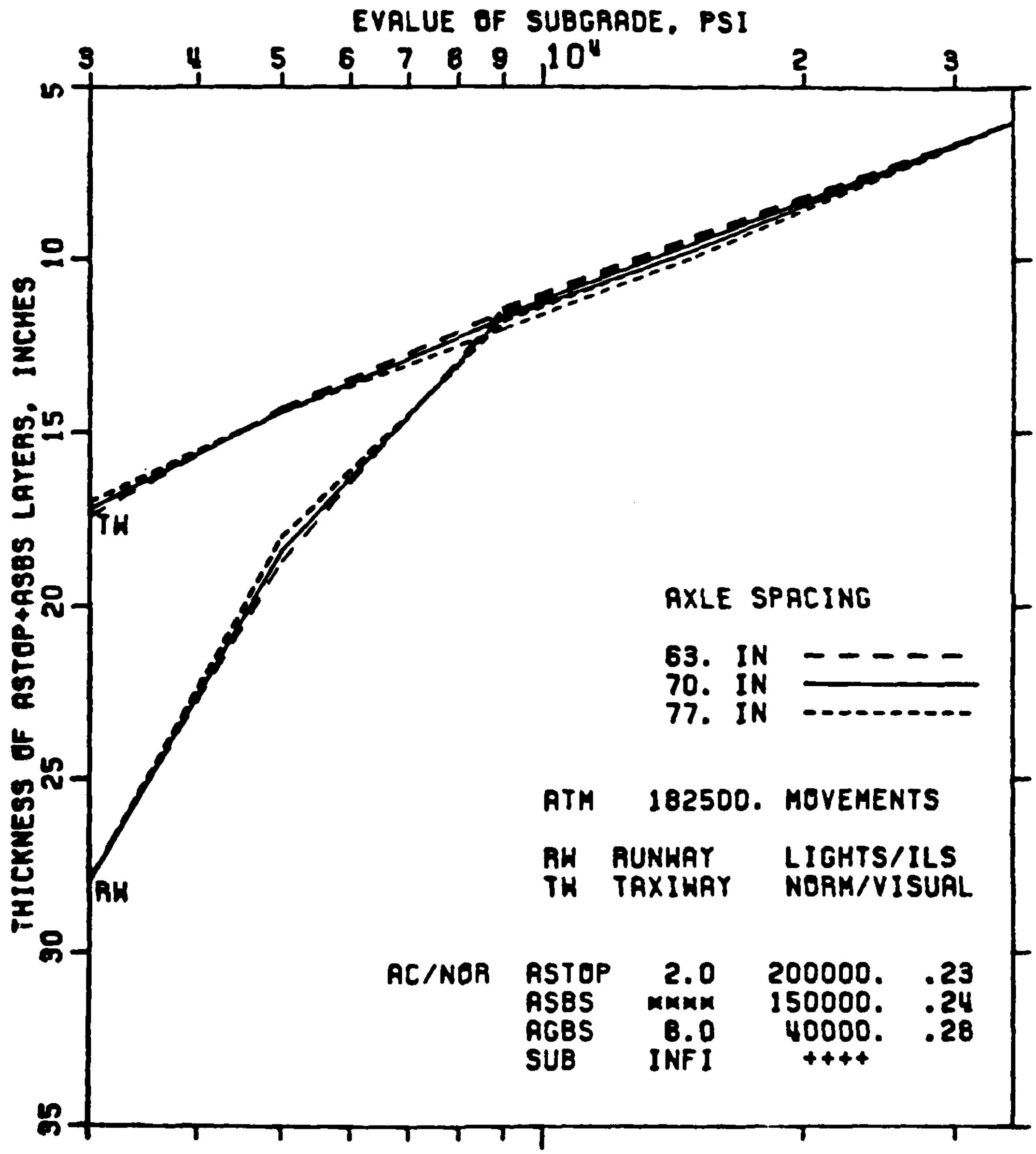

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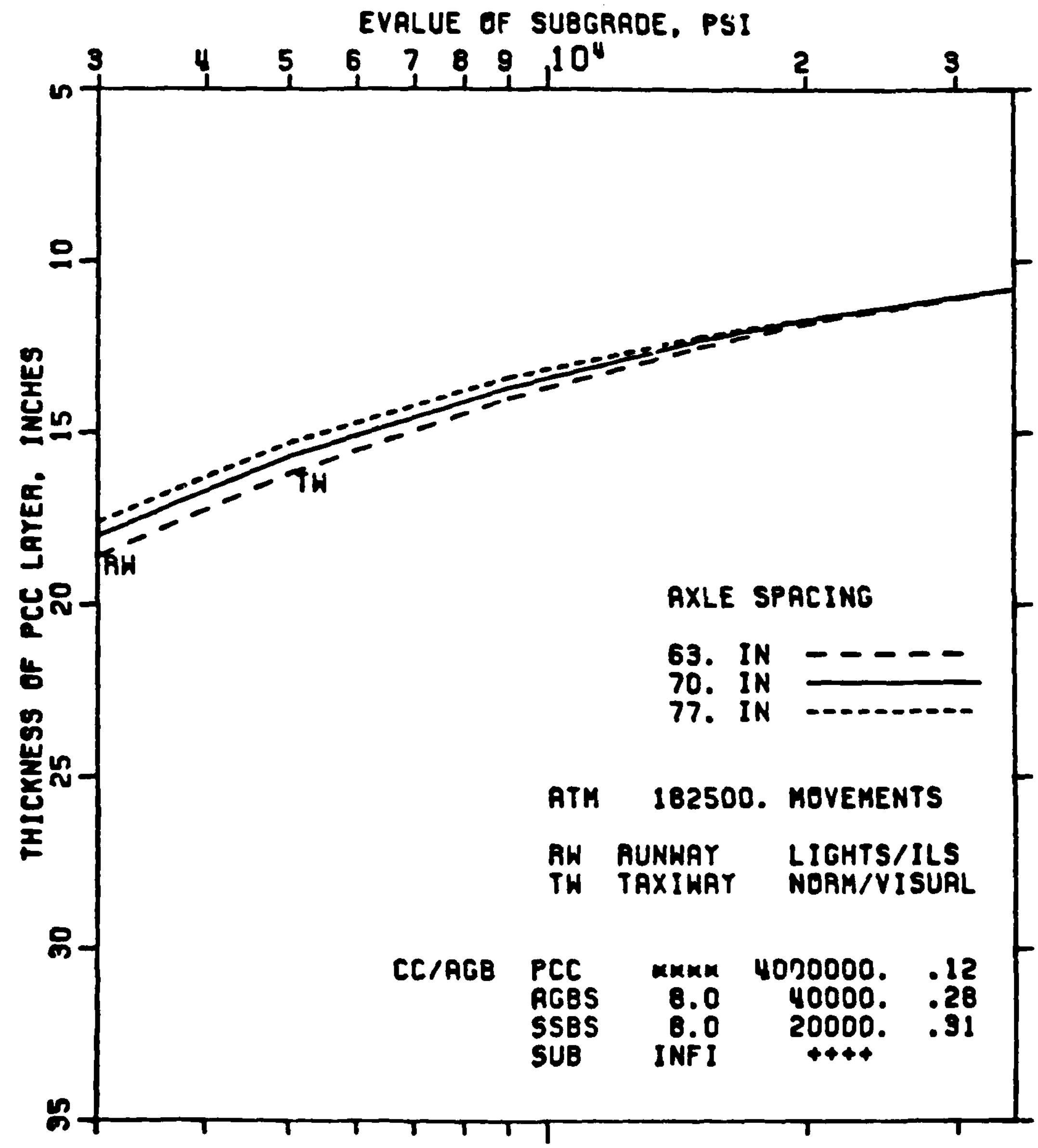

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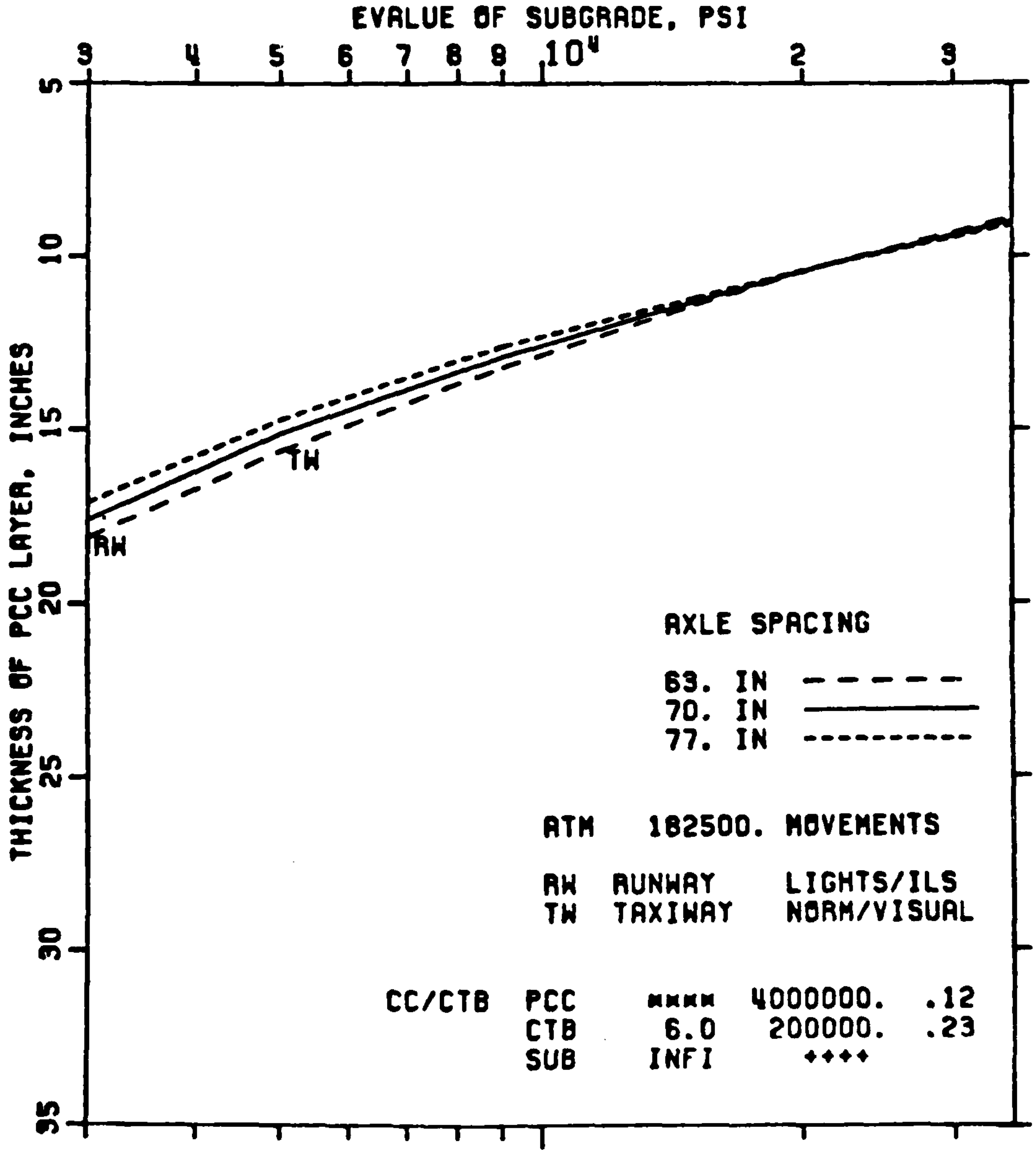

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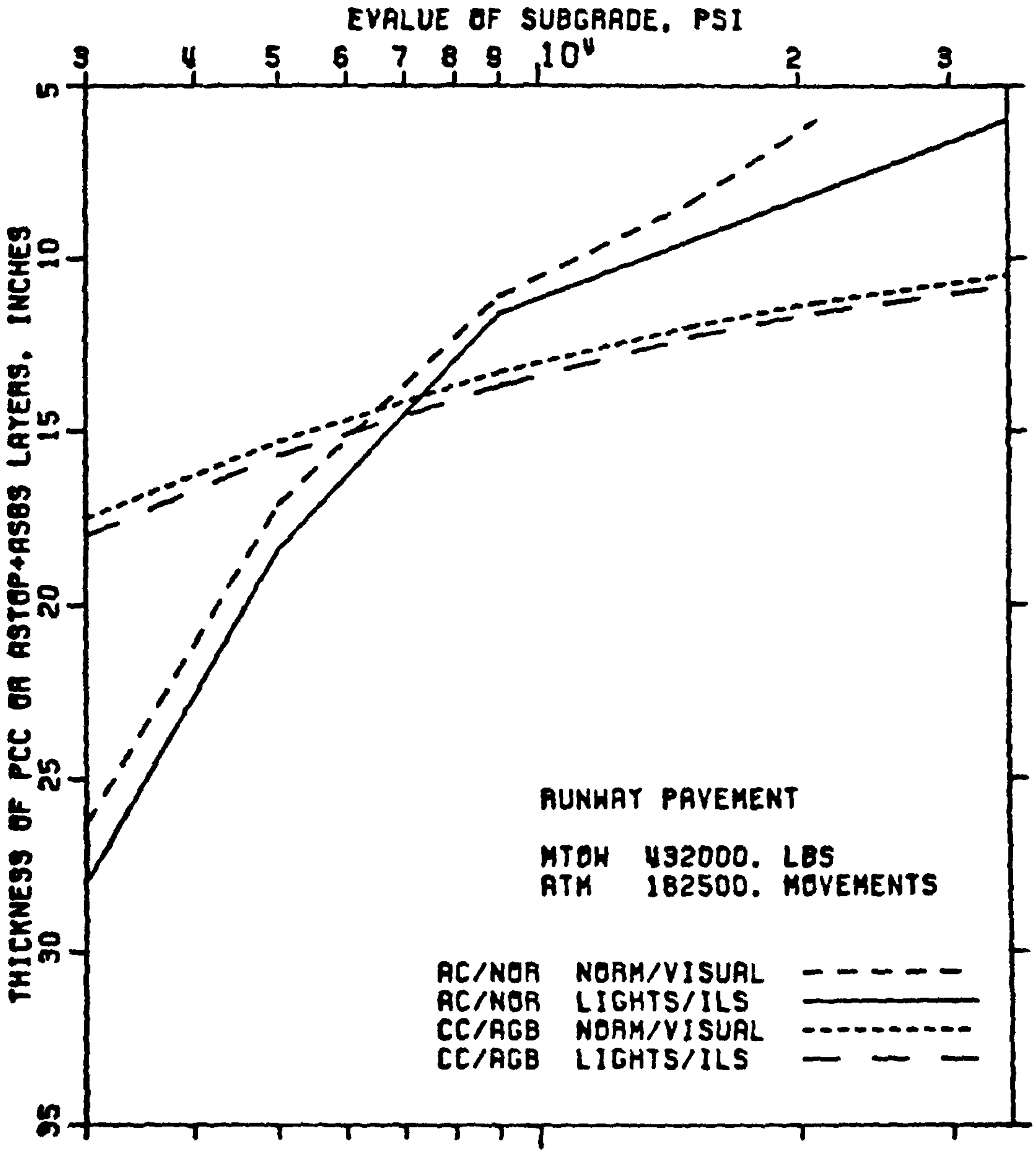

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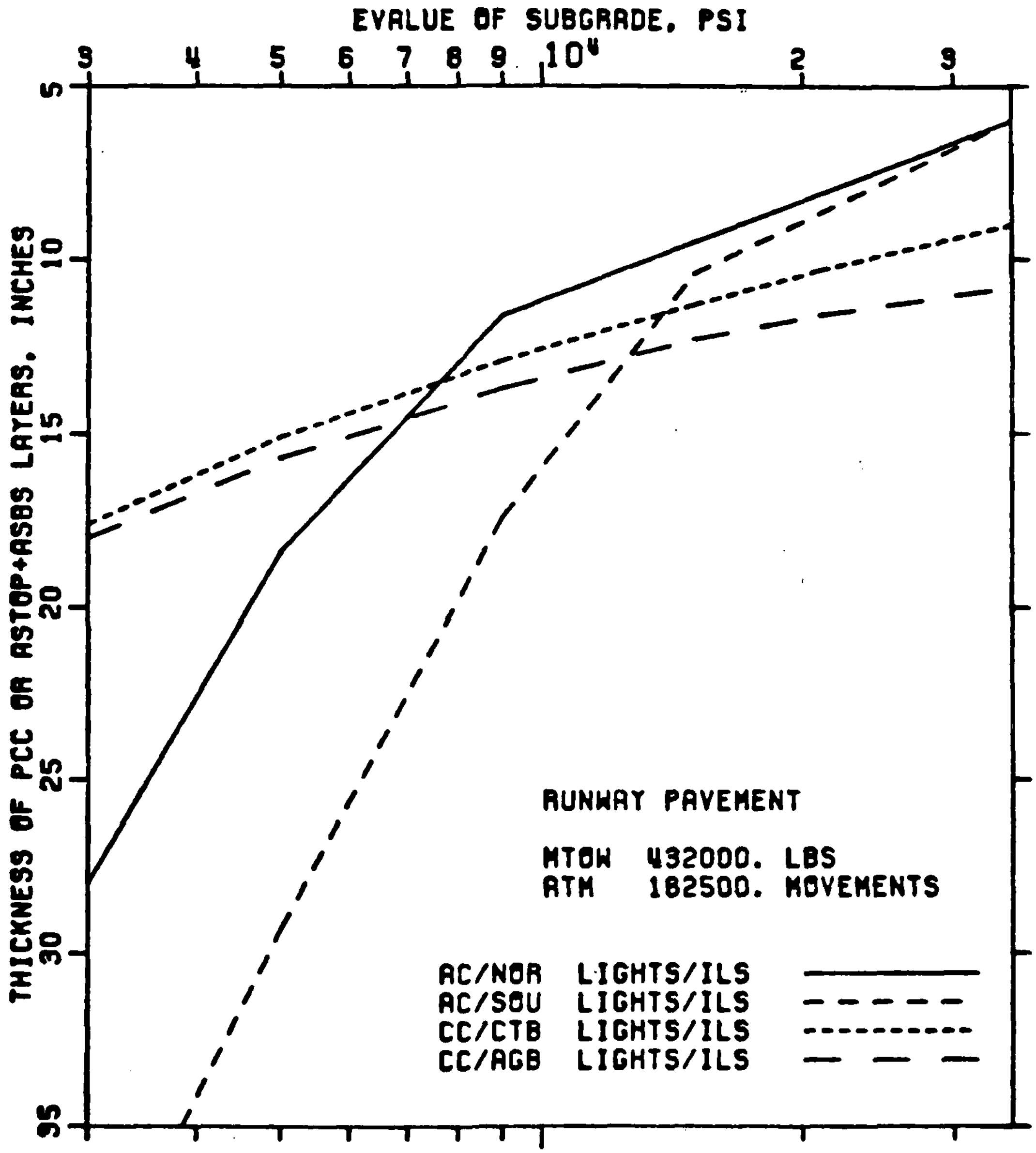

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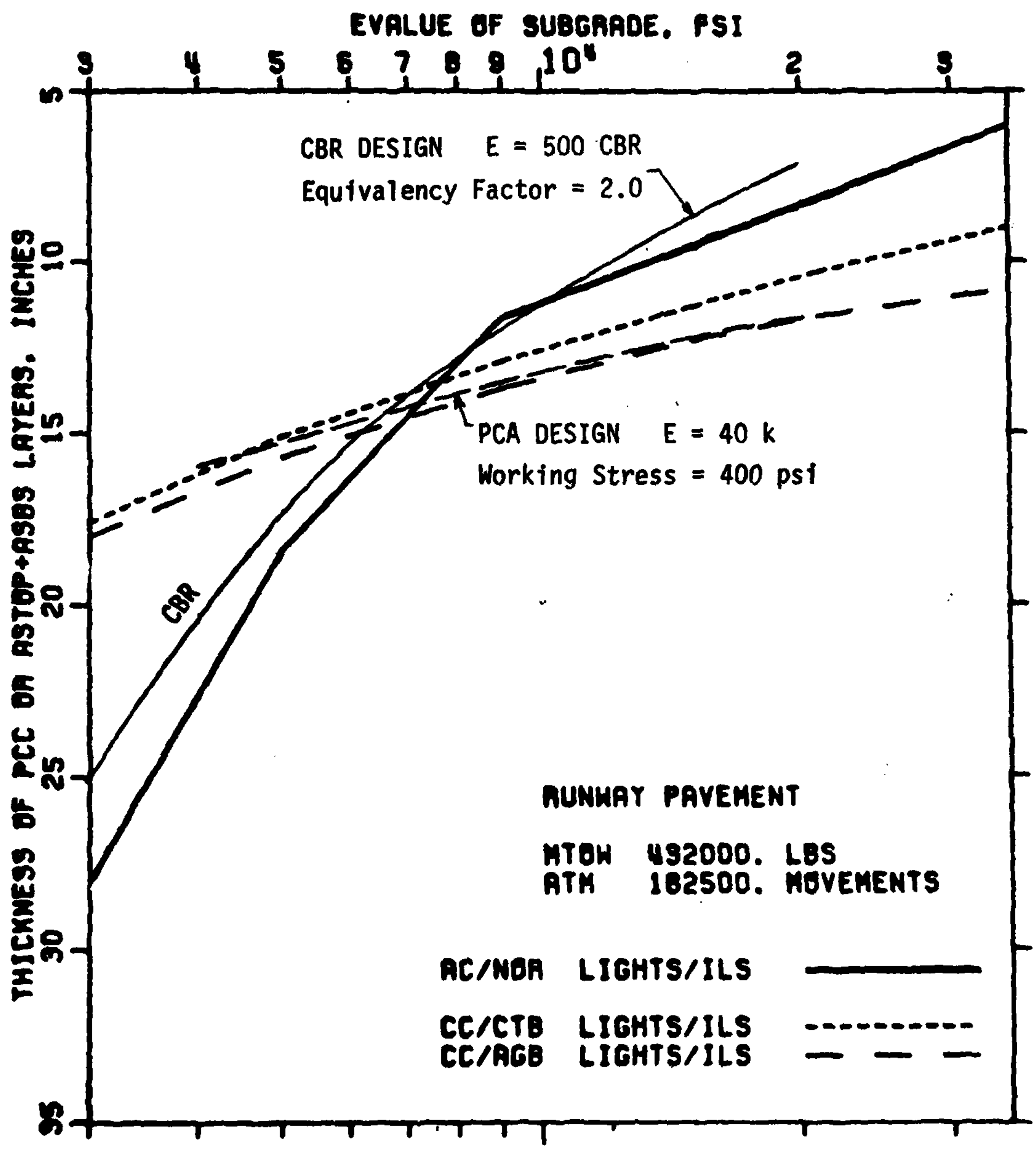

APPENDIX 4 DICTIONARY OF COMPUTER PROGRAM CODES AND IDENTIFIERS

AAND	Equivalent load repetitions of all aircraft - deflection criteria
AANS	Equivalent load repetitions of all aircraft - stress criteria
AC	Asphalt pavement
AC/AC	Asphalt overlay on existing asphalt pavement
AC/CC	Asphalt overlay on existing concrete pavement
AC/CCA	Asphalt overlay on concrete pavement
AC/PAV	Asphalt overlay
ACC	Asphalt pavement with CTB
ACE	FAA central region
ACSTR	Actual working tensile stress
AC1	3 in. EXAC
AC2	6 in. EXAC
AC3	9 in. EXAC
AC4	12 in. EXAC
AC5	16 in. EXAC
AC6	20 in. EXAC
ADM	Average daily movement
ADMAPO	Average daily movement prepared by airport operator
ADMATA	Average daily movement prepared by ATA
ADMFAA	Average daily movement prepared by FAA
ADMSUG	Average daily movement suggested for pavement design
AEA	FAA eastern region
AEU	FAA European region
AGBS	Aggregate base course, P-206 to P-214, P-217
AGL	FAA Great Lakes region
AIRB	Annual interest rate of bond
ALF	Aircraft load factor
AMC	Annual maintenance cost, $/s.y.
AND	Equivalent load repetitions of one type of aircraft - deflection
ANDA	Anticipated service life in load repetitions - deflection criteria
ANE	FAA New England region
ANS	Equivalent load repetitions of one type of aircraft - stress criteria
ANW	FAA northwest region
APX	Transverse direction probability distribution of wheel load
APY	Longitudinal direction probability distribution of landing impact
ARCD	Annual rate of cash discount
AREA-E	Mean value minus one standard deviation of a group of E-value
ARM	FAA Rocky Mountain region
ASBS	Asphalt base course, P-201
ASCCC	Rate of annual escalation of construction cost
ASCLT	Cost of asphalt oil, car load per ton
ASCMC	Rate of annual escalation of maintenance need
ASO	FAA southern region
ASTB	Asphalt treated base, P-215, P-216
ASTOP	Asphalt top course, P-401, P-408
ASW	FAA southwest region
ATD	Airport traffic distribution
ATDAPO	Airport traffic distribution prepared by airport operator
ATDSUG	Airport traffic distribution suggested for pavement design
ATM	Aircraft traffic movements

AWE	FAA western region
A1,A2	Coefficients of transfer function (transverse to long. deflection)
C	Center line
CALIB	The calibration identification number
CC	Concrete pavement
CC/AC	Concrete overlay on existing asphalt pavement
CC/CC	Concrete overlay on existing concrete pavement
CC/PAV	Concrete overlay
CCA	Concrete pavement with AGBS
CCL	Rolled lean concrete base pavement
CC1	8 in. EXPC
CC2	10 in. EXPC
CC3	12 in. EXPC
CC4	14 in. EXPC
CC5	15 in. EXPC
CC6	16 in. EXPC
CC7	17 in. EXPC
CED	Computed engineering data
CLHR	Rate of common labor per hour
COAGT	Cost of coarse aggregate per ton
COBEN	Cost benefit program
COVAR	Coefficient of variance - material strength
CTB	Cement treated base, P-301, P-304
DC	Coeff. of contact rigidity
DEF/DI	Pavement function governed by surface deflection and aircraft vibration
DEF/WZ	Pavement function governed by surface deflection
DI	Dynamic increment of aircraft vibration at pavement-wheel interface
DRY	Dry base
DSM(W)	Dynamic stiffness modulus defined by WES
DSM(1)	F(1)/Z(1) at first resonance
D1,D2	Coefficients of transfer function (elastic to cumulative deformation)
D3	Coefficient D2 at initial stage of transverse deformation for PFL study
E-SUP	E-value of pavement support (subgrade or existing pavement)
END	End portion of runway at landing roll
EPAV	E-value of existing pavement
EPW	Operating empty weight of aircraft
ESUB	E-value of subgrade
ESW	Equivalent single wheel load
ESWL	Equivalent single wheel load
EVALUE	Modulus of elasticity of response system in NDT program
EVAL	Modulus of elasticity of response system in NDT program
EXACOV	Existing asphalt overlay
EXAC	Existing asphalt layer
EXBSA	Existing base of asphalt pavement
EXBSC	Existing base of concrete pavement
EXPCOV	Existing portland cement concrete overlay
EXPC	Existing portland cement concrete layer
F(I)	Forcing function, double amplitude in pounds
FACTOR	Influence factor of all aircraft wheels
FAM	Forecast of aircraft movement
FAM*2	Double volume of FAM for pavement design
FAM/2	One half volume of FAM for pavement design

FAMAPO	Forecast of aircraft movement prepared by airport operator
FAMATA	Forecast of aircraft movement prepared by Air Transport Association
FAMSUG	Forecast of aircraft movement suggested for pavement design
FATIST	Coefficient of fatigue stress (log cycle)
FIAGT	Cost of fine aggregate per ton
FREQ	Natural frequency of aircraft gear support on pavement
GELS	General equilibrium layer system program
H(I)	Frequency of forcing function in Hz at Ith test
H(1)	H(I) at first resonance, Hz
HLBT	Cost of hydrated lime, bulk per ton
HP	Holding pad
HSTEP	Frequency scale of frequency response plot,Z(I)/F(I) vs H(I)
HSTRS	Stress at design layer of pavement model from GELS
ICC	Initial construction cost of total pavement, $/s.y.
ILS	Instrument landing system
INFI	Semi-infinite thickness of support layer of pavement model
INPUT	Summary of all input parameters
IWFAT	Cost of industry waste fine aggregate per ton
KEEL	Center strip of runway or taxiway
L	Left of center line
LBBM	Cost of construction lumber per board measure
LC/PAV	LCF overlay
LCF	Lime-cement-flyash pavement
LCF/AC	LCF overlay on existing asphalt pavement
LCF/CC	LCF overlay on existing concrete pavement
LCFA	LCF-A mix with natural aggregate
LCFB	LCF-B mix with natural aggregate
LCFC	LCF-C mix with natural aggregate
LCFSA	LCFS-A mix with industry waste aggregate
LCFSB	LCFS-B mix with industry waste aggregate
LCFSC	LCFS-C mix with industry waste aggregate
LCFS	LCF with industry waste as pavement aggregate
LIGHTS	In pavement lighting system
LOC	Location
LRW	Landing roll weight
LTSUB	Lime treated subgrade, P-155
MID	Mid portion of runway or taxiway
MLG	Main landing gear load of aircraft
MLRW	Max. landing weight of aircraft
MOD	Mobilization and demobilization cost of material processing facilities
MOD(N)	MOD for normal size of runway and taxiway construction
MOD(S)	MOD for small size of construction program
MTOW	Max. takeoff weight of aircraft
MWFPRT	Summary of FAM stresses and deflections from GELS
MWPPRT	Summary of PFL stresses and deflections from GELS
MWPRT	Summary of pavement design thicknesses from GELS
NSL	Maturity of revenue bond, number of years
NDT	Nondestructive test program
NORM	Normal airport navigation signs
NORM	Normal dry operation
NSLP	Effective functional life of pavement, number of years

NWHEEL	Number of MLG wheels per aircraft
OC1	4 in. EXACOV on 8 in. EXPC
OC2	4 in. EXACOV on 10 in. EXPC
OC3	4 in. EXACOV on 12 in. EXPC
OC4	6 in. EXACOV on 10 in. EXPC
OC5	6 in. EXACOV on 12 in. EXPC
OC6	6 in. EXPCOV on 10 in. EXPC
OC7	6 in. EXPCOV on 12 in. EXPC
OEW	Operational empty weight of aircraft
OVSFKL	Overstress factor for keel or other undefined area
OVSFSD	Overstress factor for sides
PAV	Existing pavement
PAVDES	Pavement design program
PCBT	Cost of portland cement, bulk per ton
PCC	Portland cement concrete, P-501
PCCR	Reinforced portland cement concrete, P-501, P-610
PCV	Present cash value of total pavement during service life, $/s.y.
PFL	Present functional life in years of aircraft movement(ANDA/AAND)
PFLPAV	Existing pavement for PFL analysis
PLF	Boarding factor
POZBT	Cost of pozzolan or flyash, bulk per ton
PSI	Tire Pressure
R	Right of center line
RGF	Range factor
RLC	Rolled lean concrete
RPWT	Ramp weight of aircraft
RSWLB	Cost of reinforcing steel (wire mesh) per pound
RW	Runway
SBFC	Side factor for uniform pavement cross-section
SERVYR	Design functional (service) life in years
SFST	Cost of selected fill sand per ton
SIGMAT	Horizontal tensile stress in pavement component
SLEHR	Rate of skilled equipment operator per hour
SSBS	Selected sub-base, P-154
STR/MT	Pavement function governed by working stress and maintenance needs
SUB	Subgrade support
SUMZ	Static surface deflection as computed by NDT program
TD	Touch down area
TDW	Tough down weight
TM	Terminal
TOW	Take-off weight
TW	Taxiway
ULSTR	Ultimate safe tensile stress
VEL	Velocity of aircraft
WAPCV	Weighted average of present cash value
WGT	Weight of MLG per tire
WOSTR	Safe working tensile stress
WZ	Surface deflection on pavement
XMAX	Distance between outermost wheels
XNZ	Transverse wheel spacing of the landing gear
XTW	Cross Taxiway
Z(I)	Dynamic response of SUB or PAV in inch at Ith test
ZDEF	Surface deflection of pavement model from GELS